High Power Flashlamps in Dermatology

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Abstract

Tattoo removal has long been a vexing problem. Although many methods have been involved, most of them are destructive and frequently cause scarring. However Q-switched ruby lasers have been successfully used to remove blue and black tattoos without the usual risks of textural change or scarring (Reid *et al* 1983). The major difference between this method and the others is that radiation from this laser induces preferential injury to cells containing tattoo pigment only. A major disadvantage of this method is the very high cost of the equipment, and in additional the red tattoos do not respond to red ruby light.

This thesis investigates using a high power density xenon flashlamp for the removal of tattoos. The proposed method is based on the same principle as the Q-switched ruby laser, but has potential to remove various coloured tattoos, and to cost rather less than one tenth of the cost of a Q-switched ruby laser.

In this thesis the spectral match between absorption of tattoo dyes and radiation of xenon flashlamp has been analysed. I suggest suitable treatment parameters for removal of tattoo using selective photothermolysis after calculation base on some histological studies.

The theory of the xenon flashlamp system was analysed in order to design a flashlamp system, and some experimental trials on different pulse durations and brightness were carried out.

I report on preliminary clinical trials on a volunteer's tattoos, using different pulse length and energy densities produced by various xenon flashlamps. The overall findings given by our preliminary experiments confirm that a xenon flashlamp with an appropriate energy density and pulse duration can selectively induce responses in a tattooed area by the mechanism of selective photothermolysis. These clinical trials suggest that an energy density of 8 J cm^{-2} is probably the useful treatment threshold for 100 μs pulses.

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CHAPTER 1

Introduction

Tattooing has been practised for at least two thousand years. Artists and scientists have been improving equipment and dyes gradually. Much effort has been exerted in attempting to make tattoos brighter, more colourful and stable. Today, excellent tattooing equipment and nearly one hundred colours of commercial tattoo dyes (Spaulding & Rogers catalogue 1988, 1989-1990, 1991-1992) are used in making tattoos. On the other hand, tattoo removal is as old as tattooing itself. Scientists and doctors have been searching for a successful means of removing or concealing tattoos, using traditional methods such as rubbing with salt, intradermal injection of chemical irritants, retattooing with flesh coloured pigment or using modern techniques such as irradiation by laser light.

Many individuals with tattoos want to have them removed without scarring. Reasons for tattoo removal include inability to obtain sophisticated employment, a desire for dissociation from previous imprisonment, or to improve social state and the distaste of family and friends. Sometimes there is a need to remove medical complications caused by the tattoo.

The problem of satisfactory tattoo removal with acceptable cosmetic results remains one of the unsolved areas in plastic surgery. Although many techniques have been used, no single modality has emerged as the dominant one and thus many methods have evolved. Most of the methods that have been employed over the years cause significant discomfort at the time of the procedure, produce an open wound that will require some period of time for healing and will typically replace the original tattoo with a permanent scar. In some cases, depending upon the anatomic location and individual wound healing characteristics, the resulting scar may be hypertrophic or even keloidal in nature, leaving the person more disfigured than with the original tattoo. However, many people prefer a scar to a tattoo.

For years, much work has been done in an attempt to find an effective form of tattoo removal that did not have the negative consequences of traditional methods.

Various laser techniques for the tattoo removal have been under development since the mid 1960s. Laser tattoo removal was initially reported by Goldman *et al* (1963, 1965, 1967) who performed experimental treatment of many lesions, including tattoos, with different lasers. non-Q-switched and Q-switched ruby, carbon dioxide and argon lasers, and lasers combined with chemicals have all been studied for the removal of tattoo. However, except for the Q-switched ruby laser, they still can not overcome the main disadvantage of producing the scarring which the traditional methods also cause. Q-switched ruby laser tattoo removal has a different mechanism from that of other lasers.

One laser therapy mechanism is thermocoagulation. Localised burning of tattooed and non-tattooed skin is induced by using a focussed carbon dioxide or argon continuous output laser. Although the argon laser acts initially by selective absorption, the actual effect of both lasers is to dermabrade the skin layer by layer with the tattoo pigment being removed. However, an open wound is created and post-treatment care is necessary. Complications of this type of laser treatment include hypertrophic scarring and residual tattoo pigmentation in most cases.

In the early 1980's, clinical research performed in Scotland indicated that the Q-switched ruby laser could be used successfully to remove blue and black tattoos, particularly amateur tattoos, without the usual risks of textural change or scarring (Reid *et al* 1983). A later article, 'Q-switched ruby laser treatment of tattoos; 9-year experience' further reported that both amateur and professional tattoos responded favourably to treatment, with a few professional tattoos being completely removed (Reid *et al* 1990). This laser produces a pulse of 4 J with a length of 30 ns to 40 ns. In recent years, Q-switched ruby lasers have been used in clinical treatment in several places around the world. The nearest clinical laser to New Zealand was in Sydney. Dr. Bill White worked for Dr. A Scheibner in Sydney, using a Q-switched ruby laser to remove tattoos for 3 years. Many successful cases were achieved, Figures 1.1 and 1.2 show pictures before and after treatment which were provided by Dr. White.

One advantage of the Q-switched ruby laser is that an open wound is not created and the skin usually can return to normal texture and normal colour without scarring. This is the major difference from the destructive therapies. However, some disadvantages cannot be overcome as they are inherent in the characteristics of this type of laser. The major disadvantage is the high cost of the equipment. Slow, tedious treatment is a second disadvantage. A third disadvantage is that this laser cannot be used for the removal of red tattoos, because the ruby laser emits light of wavelength 694.3nm. The details will be described in Chapter 2.

The mechanisms by which the Q-switched ruby laser is able to provide such beneficial results are unclear and are being explored. There is no general consensus at this time and many different explanations have been proposed.

Figure 1.1 An professional tattoo before treatment

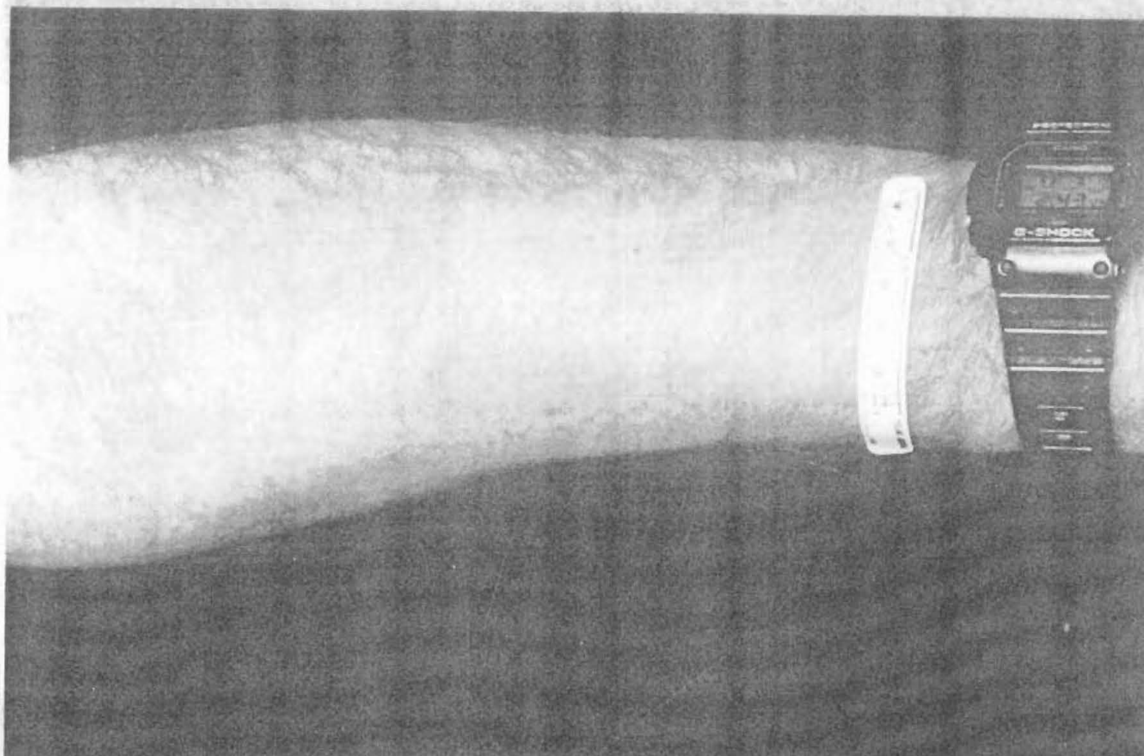


Figure 1.2 An professional tattoo completely removed without apparent scarring

One theory, which has been advanced by most authors, is that this therapy mainly works by a mechanism that is often called selective photothermolysis. Incident radiation is selectively absorbed by the target in the skin. The resultant temperature rise causes injury to the target. Previous studies in this Department (Pickering 1990, Halewyn 1987) have analysed the treatment of vascular lesions, where yellow light absorbed by haemoglobin is used to cook the endothelial wall of the enlarged blood vessels. It is less clear that similar processes are involved when using a Q-switched ruby laser to treat tattoos.

There is agreement that the first step of the process is the selective absorption of ruby laser energy by carbon black and the various metallic dyes used in the creation of tattoos. However Reid *et al* (1983, 1990) propose that the best response results from a combination of at least two mechanisms. The first mechanism is that immediately the dark tattoo pigments absorb the laser energy, there is a production of steam and chemical alteration of the the ink into colourless compounds (which they suggested could be carbon dioxide or carbon monoxide). The second mechanism is that a rapid increase in temperature causes disruption of the collagen-enclosed pigment particles by vapourisation of the surrounding tissue water. The usual physiological defence mechanisms are subsequently invoked to dispose of the debris.

Taylor *et al* (1990) report the response to treatment with the Q-switched ruby laser of 36 amateur and 22 professional tattoos. They gave a few explanations of possible mechanisms responsible for the removal of tattoos, including systemic elimination through the lymphatic system, and external elimination via the scale-crust that is shed. They also put forward the hypothesis that the decrease in tattoo particles size and alteration of pigment granule structure using a 'super pulse' are sufficient to alter the optical properties of the tattoo pigment to make it less apparent. Another suggestion they made is the same as that given by Reid *et al*, that is, the extreme temperatures that occur transiently at the granules of pigment may be sufficient for pyrolytic chemical alterations of the pigments.

Scheibner *et al* (1990) propose that the favourable results obtained in treating tattoos are the result of mechanical forces or photoacoustic waves, which are generated in tissue by the high energy pulses from the ruby laser. The effect of the photoacoustic waves is to rupture the pigment granules by cavitation and fragmentation of the various metals from which they are made. Once shattered, the pigments are slowly removed by the inflammatory reaction.

We believe that the selective photothermolysis mechanism plays a major role for Q-switched ruby laser tattoo removal. But, we propose that it is not necessary to rupture individual tattoo pigment particles, because very few single tattoo pigment granules were observed in tattoo specimens in our histological study, rather tattoo particles occurred in small and big clusters (see Figure 3.3). The tattoo pigment granules, carbon based or various metals, are sealed by collagen capsules and form diverse clusters, which are in turn are in tattoo pigment containers (predominantly in fibroblasts). Breaking up the tattoo pigment clusters or containers is sufficient to scatter the particles. Then the tattoo fades gradually as the physiological defence system removes the fragments.

In Chapter 2, we will describe the various traditional and modern methods for removal of tattoos and their associated advantages and disadvantages.

In Chapter 3, we will describe the structures of normal and tattooed skin. As well, we will outline the tattooing process and discuss the tattoo dyes used for making tattoos. We also analyse three specimens of tattooed skin and present the distributions of the tattoo pigments in depth and size.

In Chapter 4, we will describe the selective photothermolysis concept and analyze the necessary conditions for applying this principle. As well, we will discuss the postulated mechanisms of how the Q-switched ruby laser treats tattoos and give an explanation as to why multiple treatments are necessary. We also do a calculation to determine the theoretical values for illumination time and the energy intensity required to break up tattoo pigment clusters.

In Chapter 5, we will present the output spectrum distribution from a xenon flashlamp and absorption spectrum of several tattoo dyes measured in our experiment, and discuss the spectrum match between xenon flashlamp radiation and tattoo dyes absorption. We outline exposure limits to ultra-violet on the skin because the radiation of the xenon flashlamp contains UV. In order to satisfy the standard for exposure to ultraviolet when using a xenon flashlamp for removal of tattoos, the transmission spectra of the three kinds of UV glass filter are measured and discussed.

The Q-switched ruby laser has a pulse duration of 30 to 40 ns (Taylor *et al* 1990). This thesis argues that such a short pulse duration may not be necessary for the removal of tattoos. The energy density and the pulse duration required depend upon the size of the tattoo pigment clusters or containers rather than that of the particles. The pulse duration required for clusters will be calculated in Chapter 4, but initial calculations (Pickering *et al* 1989a) suggested to my supervisor that around 10 μs would be sufficient to kill the fibroblasts and other tattoo pigment containers. Therefore, he proposed a new method, using xenon flashlamps to remove tattoos.

Xenon flashlamps can produce a continuous spectrum output and a high energy intensity pulse of short duration. The output spectrum from xenon flashlamps covers the range of ultraviolet, visible and infrared. The visible spectrum region covers the strong absorption bands of various tattoo pigments, as described in Chapter 5. Xenon flashlamps are the brightest non-laser source. They may be an ideal source for tattoo removal by selective photothermolysis. Their most important advantage is that a xenon flashlamp system is less than one tenth the cost of Q-switched ruby laser equipment.

A xenon flashlamp and electrical power supply were ordered from Xenon Corp. in USA. This system did not meet the specification and could not provide the pulses that we required. The pulses produced by this system were of 20 μs duration and the maximum energy density was 2.5 J cm^{-2}. This does not meet our requirement for pulse duration of 10 μs and energy density of 10 J cm^{-2}. However, the Xenon Corp. system could not give a higher energy density output at the same pulse duration because the damage threshold of flashlamp is restricted by the pulse duration. I redesigned the discharge circuit on the original system, in order to obtain higher energy density. The modified discharge circuit provides pulses with 8 J cm^{-2} at 550 μs or 5.5 J cm^{-2} at 450 μs.

Preliminary clinical trials have been done on a volunteer's tattoos with different pulses which were produced by two xenon flashlamps. Details of the equipment and clinical experimental analysis will be described in Chapter 6. The treatment area had black, red and normal skin, the tattoos are 35 years old, are professional and had been recolored (retattooed). After radiation, the immediate and medium-term responses were similar to that produced by Q-switched ruby lasers. The experimental results also showed the response in tattooed area was much greater than in the normal skin, However, the tattoo colours were not noticeably changed after one treatment, and skin damage was a little greater than that induced by Q-switched ruby lasers. One month after treatment, the irradiated area had returned to normal. However the pulse duration of 550 μs is much longer than the theoretical value, which we calculate in Chapter 4.

The overall findings given by our preliminary experiments confirm that a xenon flashlamp with an appropriate energy density and pulse duration can selectively induce responses in a tattooed area by the mechanism of selective photothermolysis. The experimental results also suggest that the pulse duration of the xenon flashlamp should be improved to be close to the thermal relaxation time of the tattoo pigment clusters. A new xenon flashlamp with 2280 torr fill pressure and 0.3 cm thickness wall is being designed and manufactured for further trials. This flashlamp should provide pulses of 80 μs duration and maximum energy density of 10 J cm^{-2}.

In Chapter 6, we will describe the electrical characteristics of the xenon flashlamp and analyse its discharge circuit behaviour. We also discuss several trigger circuits including over-voltage, external, series and simmer trigger, and the factors which affect flashlamp lifetime and efficiency.

In Chapter 7, we will describe the equipment used in our clinical trials and characteristics of the output from the xenon flashlamps for both the original and the modified system and also report experimental phenomena of pre-clinical trials. We found that the xenon flashlamp may have a potential application of bleaching. We will describe and analyse the clinical trials which took place on three volunteers with both systems.

In Chapter 8, we will summarise the results of this thesis. First, a new method of a high power xenon flashlamp removal of tattoo is proposed for the first time. Second, we postulate the selective photothermolysis plays a major role for Q-switched ruby laser tattoo removal, and three necessary factors are presented for the application of selective photothermolysis technique. Third, there is a good spectral match between absorption of the tattoo dyes and radiation of the xenon flashlamp. Forth, we propose new treatment parameters as a result of our histological studies. Fifth, our theoretical calculation and clinical trials suggest that the pulses of the order of $100\,\mu s$ and energy density of $8\,J\ cm^{-2}$ are probably near the treatment threshold for removal of tattoos.

CHAPTER 2

History

In this chapter, we will describes various methods which have been used for removal of tattoos. As well, we will analyze how they work and their disadvantages. First, we discuss the traditional methods of tattoo removal which include surgical, mechanical, chemical and thermal treatments. And then we will talk about modern methods. Laser treatment methods have been under development since the mid 1960s (Goldman *et al* 1963, Goldman *et al* 1965, Goldman *et al* 1967). non-Q-switched and Q-switched ruby, carbon dioxide, argon and copper vapour lasers, and lasers combined with chemicals have been studied for the removal of tattoo. However, to date carbon dioxide, argon, copper vapour and Q-switched ruby lasers have been used clinically for tattoo removal. Carbon dioxide, argon and copper vapour lasers involve some element of destruction of the superficial dermis and an open wound. This destruction produces a direct physical ablation. The Q-switched ruby laser works in a different way from carbon dioxide, argon and copper vapour lasers. This laser gives the best results of any system, usually achieving removal of tattoos with no scarring.

2.1 Motivation for tattoo removal

The reasons for requesting removal of tattoos are various, such as, numerous medical complications, religious reasons, indicating a dissociation from previous imprisonment or compromised social state, inability to obtain gainful employment or to improve cosmetic appearance.

Numerous medical complications (Abel *et al* 1972) are well known to result from tattooing. These range from septic problems to hypersensitivity reactions. Certain cutaneous diseases, such as herpes, psoriasis, lichen planus, and discoid lupus may localise in tattoo sites. Acquired hypersensitivity to tattoo pigment is well known, especially to tattoo dyes containing mercury (red), chromium (green), cobalt (blue), and cadmium (yellow) (Apfelberg *et al* 1980, Lehmann and Pierchalla 1988).

2.2 Traditional methods

2.2.1 Surgical excision

Cold knife surgical excision is a common method for the removal of a small or long, narrow tattoo (Lindsay 1989). When removing such a tattoo, the surgeon can plan an excision geometry that forms a closable shape and includes normal and tattooed skin. On the other hand, the surgeon may choose an excision geometry may be chosen that cuts as closely around the tattoo as possible. This frequently leaves quite an irregularly shaped excision defect, but it wastes a minimum of normal skin. Larger tattoos may require a series of excisions repeated at 6 monthly intervals. Excision and split-thickness skin grafting is often employed for large tattoos that have penetrated the dermis. Surgical excision, however, can result in an obvious scar in both the tattoo and donor area and can also be expensive. Mr. E. P. Walker, who regularly uses excision, has provided us with samples for histological study.

2.2.2 Mechanical treatment

Mechanical methods of tattoo removal consist either of re-tattooing or of dermabrasion.

Dermabrasion with the diamond fraize or a wire brush has been used for years for the removal of tattoos. The tattoo area is anaesthetised and most operators continue the dermabrasion at the initial sitting until all of the tattoo pigment is removed. This sometime results in excessive scar formation.

In 1975, Clabaugh described his experience in removing tattoos by dermabrasion in which he abraded the skin only deep enough to achieve partial pigment removal. The abraded wound is then painted with 2% aqueous gentian violet and then adaptic gauze is applied to the denuded surface (Clabaugh 1975). The key aim of both dermabrasion and the use of the chemical is to prolong the healing process with increased inflammation, so that a phagocytic response will result in the expulsion of the pigment. However, prolonged epithelization, while being helpful with pigment removal, can increase scarring and disrupt the normal pigmentation by melanin.

2.2.3 Thermal treatment

Thermal methods include both cautery and cryosurgery (Apfelberg and Manchester 1987). Thermal injury, such as that resulting from fire, hot coals, or even cigarettes, has been used for centuries to obliterate tattoos. Electro-desiccation and electrocautery with a low power setting, causing superficial damage to the skin, have been used for tattoo removal but yield scarring for a large percentage of patients. Liquid nitrogen has also been used to remove tattoos. However, atrophic and depressed areas of skin often result.

2.2.4 Chemical treatment of tattoos

Caustic chemicals have been used for tattoo removal since as early as 543 AD. The Greek physician Aetius described a mixture of one part of pepper, two parts of rue and two parts of orpiment, with unspecified quantities of nitre and turpentine resin. This was applied to the tattooed area (Scutt 1972). Once all the tattoo pigment was removed, a fresh layer of the unction was applied with a feather. After twenty days, there was a large ulcer without any of original marks remaining. However, scarring was inevitable.

The various effective methods rely on the use of chemical irritants (Scutt 1972, Hudson and Lechtape-Gruter 1990), such as pricking into the tattooed area a solution of tannic acid and ending up with rubbing silver nitrate over the top, using pure potassium permanganate powder inserted into the dermis through multiple superficial incision, or using trichloroacetic acid, or phenol with and without gentian violet. However, the complications are difficult to predict. Hyper-pigmentation and ugly scars occur frequently.

2.3 Laser removal of tattoos

2.3.1 Argon laser tattoo removal

The argon laser has been used in the treatment of decorative tattoos (Apfelberg and Maser 1979). This laser produces light principally of wavelengths 488nm and 514nm. Initially there is selective absorption by tattoo pigment granules in the upper dermis. Because this laser operates at low power and long exposure, after some carbonization of the epidermis has occurred, there is non-selective absorption. This results in some immediate ejection of pigment through the skin. It is evident that an open wound is created. The resulting charred tissue was left untouched and the wound was dressed with ilotycin ointment and left open to the air. Patients are advised to cleanse the wound with hydrogen peroxide and to use the ilotycin dressing once daily until separation of all eschar. General or local anaesthetic is required before treatment. Limitations of argon laser treatment of tattoos include the following, 100 per cent change in skin texture, 20 per cent incidence of hypertrophic scarring, and 75 per cent incidence of 'ghost' or residual pigmentation (Apfelberg *et al* 1980). Mr. E. P. Walker has used a copper vapour laser in the same way, with similar results.

The 'chemo-laser' technique embodying the use of chemical agents and the laser treatment was developed in 1981 – 1982. This method has shortened the number of visits for laser treatment of large tattoos. This method was reported as follows. After argon laser dermabrasion, the skin surface is cleansed with isopropyl alchhol. Cotton swabs are used with 100% acetone to cleanse the area of tattoo dye. An application of 40 to 50% urea in petrolatum base is effectuated to the entire area for occlusion. The dressing is left for one week. The area is then dressed with same urea mixture covered for another week. All patients observe dye on the cotton gauze. Some patients report soreness. Dismukes (1986) concludes that the effectiveness of argon laser removal of tattoo can be enhanced with use of agents, and that the number of visits is reduced to two or three sessions compared with five to eight visits required previously.

2.3.2 Tattoo removal with the carbon dioxide laser

Tattoo removal with the carbon dioxide laser has been reported by many authors (Brady *et al* 1979, Reid and Muller 1980, Apfelberg *et al* 1985). The carbon dioxide laser produces continuous light in the infrared spectrum at 10,600nm. The absorption coefficient of carbon dioxide laser in tissue is very high— the value generally used is 200 cm^{-1} (Carruth and Mckenzie 1986). In other words, light from a carbon dioxide laser will be 90% absorbed within a distance of only $100\mu m$. This thickness of tissue is only a few cell widths, which will very quickly be heated to 100 °C. Thus, the carbon dioxide laser can be used to shave cell layers in a very selective manner. The initial treatment consists of applying a 'brushwork' at approximately 10 watts in order to remove the superficial layers of the epidermis. This layer is then mechanically cleansed with a saline peroxide solution, and a more specific application to the underlying upper dermis with its enclosed tattoo pigment is then started under microscopic control or magnification. As each layer of skin is progressively irradiated, that layer is then cleansed, and only residual pigmentation particles are exposed. The carbon dioxide laser is used to dermabrade the skin layer by layer effectively through the process of thermocoagulation and vaporisation of specific lesions. Therefore, one can produce a very selective dermabrasion of skin until the lowest pigmentation has been vaporised. An open wound is created. Postoperative care is usually identical to that after argon laser treatment. Complications of carbon dioxide laser treatment include hypertrophic scarring and residual tattoo pigmentation in many cases. Some clinicians used chemical agents after carbon dioxide laser dermabrasion in the same way as described for argon lasers (C Vinciullo 1991, private communication).

2.3.3 Q-switched ruby laser removal of tattoos

Q-switched ruby lasers have been used for removal of tattoo in clinical treatment for many years. The clinical version of this laser produces a 'super-pulse' of 4J with a wavelength of 694.3nm. This corresponds to very high peak powers because the pulse duration of this laser is in the range of 30 to 40 ns. It has been reported that the power densities of 120 to 280 MW cm^{-2} are most suitable for tattoo removal. A number of repeat treatments is necessary, with more repeats for completely removing professional tattoos than for amateur tattoos.

The advantages of this technique for removal of tattoos are dramatic. First, the skin returns to normal texture and normal colour without scarring. Second, there is little need for postoperative care, because an open wound is not created. However, often little hypo-pigmentation or hyper-pigmentation occurs.

The disadvantages are the cost of the equipment (about $NZ 300,000), and the need for repeat treatments. The equipment is very expensive, in part, because ruby (that is, C_r^{3+} doped aluminium oxide) has a three energy level system, and so has a lower efficiency than other lasers with four energy level systems, typically an efficiency of 0.5% in non-Q-switched operation. In the Q-switched operation, the efficiency is about 0.1% to 0.2%. Its output is also highly sensitive to the operating temperature, which generally limits its repetition rate. In order to overcome this, a complicated cooling system is needed. In addition, five to six piece articulated arms are needed to deliver the light to the treatment area.

Another important disadvantage is that only small treatment areas are possible. Ruby material is a specially grown single crystal material. It is expensive, particularly in large sizes, and it is difficult to obtain uniform crystal for a large size ruby laser. However, uniform light distribution is necessary for the treatment. The limits on ruby rod size result in a small treatment area and at present most instruments have 5mm diameter treatment area. This results in long treatment sessions and bring inconvenience and high cost for patients.

CHAPTER 3

The structure of skin and tattoos

An understanding of skin structure is necessary to enable discussion about the interaction of light radiation with tattooed skin. We shall outline in this chapter the structure of normal skin–epidermis, dermis, hypodermis, dermal cells and blood vessels. We present analyses of tattooed skin and describe the tattooing process and tattoo dyes used for making both professional and amateur tattoos. As well, we will analyse tattoo pigment cluster distributions in depth and size in the tattooed skin.

3.1 Normal skin structure

The skin is the largest organ in the body, constituting approximately one-eighth of the weight of a normal individual. Its attachment to the body varies. The epidermis, dermis, and adipose make up the skin's three distinct layers. Figure 3.1 is a diagram showing the structure of normal skin.

3.1.1 Epidermis

The epidermis is the outermost layer of the skin. Five sub-layers of cells [1] may be recognised histologically. The epidermis is cellular and avascular and is 60 μm to 100 μm thick in most regions, but tending to be thicker on the back and much thicker in callussed areas.

The epidermis is continually producing new cells being shed, from the time the embryo has an epidermis until the individual is dead. The growth of epidermal appendages such as nails and hair is also essentially continuous throughout life. The very lowest sub-layer of the epidermis, the basal layer, consists of two types of cells, melanocytes and keratinocytes. The melanocytes produce small egg shaped sacks which are called melanosomes, and contain the chromophore, melanin. These melanosomes are distributed by the melanocytes throughout the keratinocytes. It is

[1] stratum basal; stratum germinativum; stratum granulosum; stratum lucidum; stratum corneum.

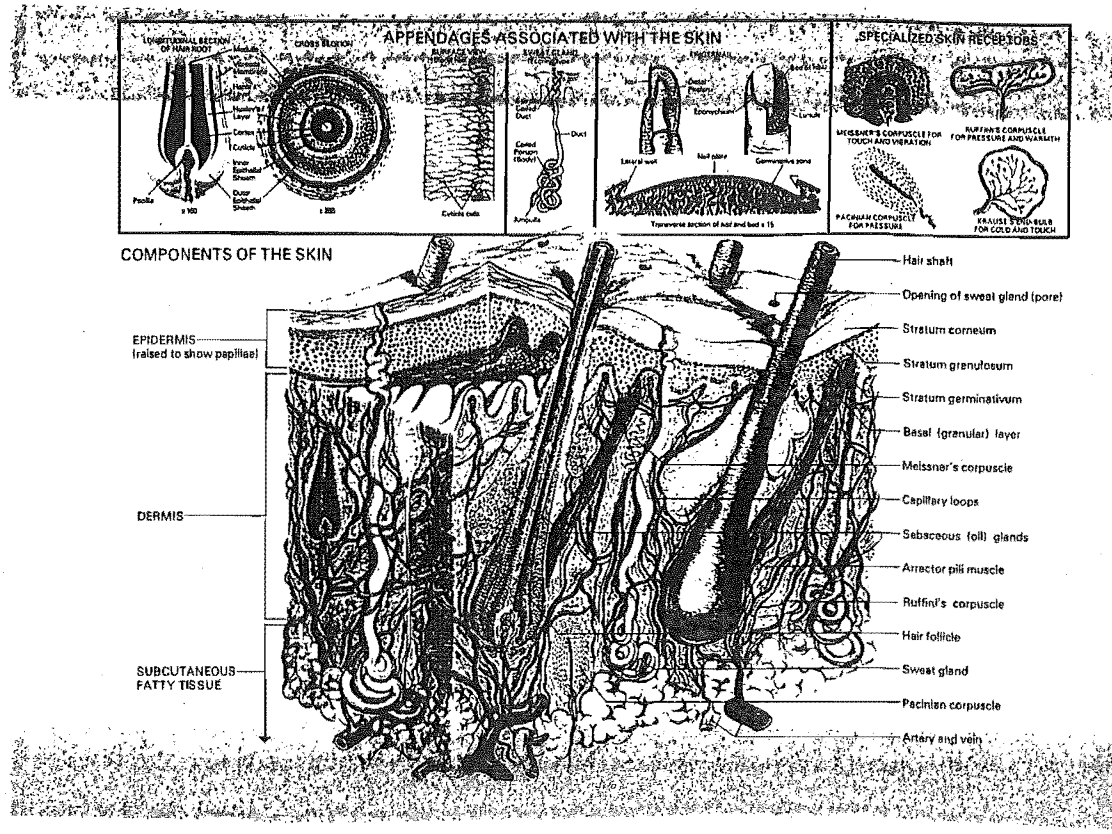


Figure 3.1 Structure of skin

the melanin which gives us our yellow, brown, or black pigmentation and protects us from ultraviolet and visible radiation. These cells are joined to a basement membrane which marks the junction between the epidermis and dermis. In vertical section this junction presents a wavy appearance (see Figure 3.1) because of the dermal papillae. Cells are produced from the basal layer by mitosis and these move outward, finally to be shed from the surface as fully keratinized dead squames. A typical cell takes 2 to 3 weeks to pass from the basal layer to the surface, and in the course of its journey it undergoes a number of transitions, leading to the characteristic histological appearance of the cells at each level.

3.1.2 Dermis

The lower connective tissue layer is the dermis varies from 2mm to 4mm thick and forms the bulk of the skin. It contains the cutaneous appendages (hair folicles, sebaceous and sweat glands) and blood vessels. It is a tough, resilient tissue that cushions underlying organs against mechanical injury and provides nourishment for the epidermis and cutaneous appendages. The main structural feature of the dermis is a network of mechanically strong fibres, mostly collagen, but with some elastin, embedded in a matrix of amorphous ground substance. The fibres (collagen, elastin) are protein and the ground substance is polysaccharide. In contrast to the epidermis which is almost entirely cellular, the dermis contains few cells. Those present are mast cells, macrophages, lymphocytes and melanocytes.

3.1.3 Hypodermis

Beneath the dermis is third layer of the skin. It is a layer of loose connective tissue called the subcutaneous fatty tissue or hypodermis. Over most the body it forms a layer of adipose tissue, which provides thermal insulation and mechanical protection while the fat represents an energy reserve.

3.2 Dermal cells

The dermis, in comparison with the epidermis, is poor in cells, being composed mainly of connective tissue. The most abundant cell type is the fibroblast which produces collagen, but the status of these cells in relation to the production of elastin is less clear and while some authorities maintain that fibroblasts produce all the materials of the extracellular matrix, others hold that spatial cells produce the glycosaminoglycans (Wood and Bladon 1985).

Mast cells are common in connective tissue, including the dermis, along with macrophages. Macrophages, also called wandering histiocytes or phagocytic cells, originate from blood stem cells . In some connective tissue they are almost as abundant as fibroblasts from which they may be distinguished by having an indented, bean-shaped nucleus. Injection of a dye, such as colloidal trypan blue into the dermis, shows an essential difference between fibroblasts and macrophages: only the macrophages accumulate particles of the dye. This demonstrates the role of macrophages as scavengers of foreign particles, fragments of cells or extracellular material. Another difference is found in their distribution. Fibroblasts tend to occur near collagen fibres whereas macrophages tend to congregate in the region of blood vessels.

3.3 Blood supply

The cutaneous blood supply brings nourishment to the skin but it also has an important role in the regulation of body temperature. The skin itself is relatively modest in its requirements for oxygen but despite this it has a very abundant blood supply. Arteries paired with veins penetrate the subcutaneous fat and form a plexus just below the dermis. These vessels are visible on the undersurface of skin on removal. From this network, vessels rise vertically to supply the mid-dermis. Another plexus of the smallest arteries and veins are formed just below the papillary layer of the

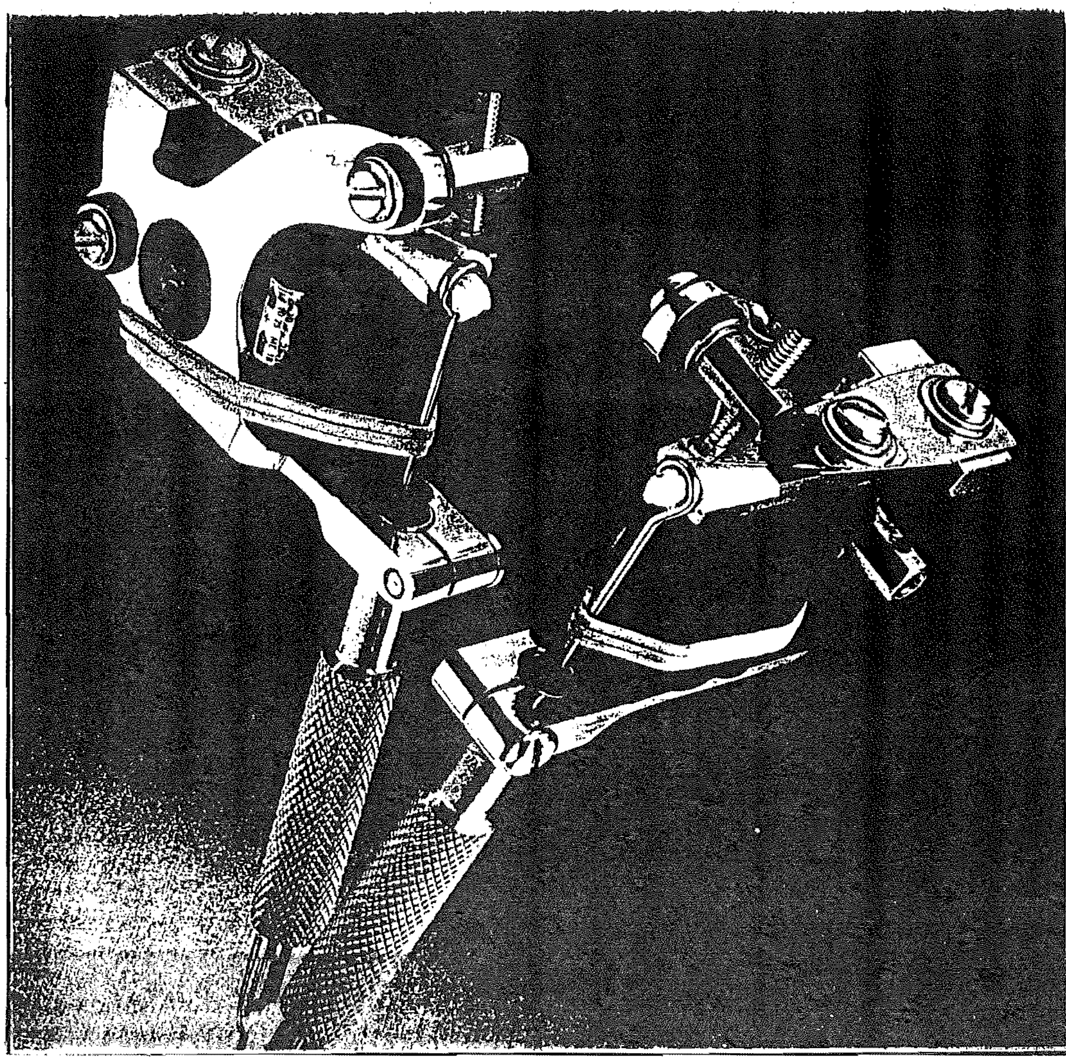


Figure 3.2 Tattooing machine

dermis. These vessels have the highest proportion of muscle in their walls and supply the glands and hair roots. Shunts provide a means of short-circuiting the capillary circulation in the dermis to prevent heat loss. Since the epidermis is avascular, it receives its supply of nourishment from the vessels in the tips of the papillae. The two vascular layers are connected by vertically oriented arterioles.

3.4 The professional tattoos

Decorative tattoos may be divided for histological purposes into two categories, professional and amateur. These categories also provide useful clues to appropriate treatment.

Professional tattoos are applied using a bunch of needles mounted on a electrical vibrator (see Figure 3.2), usually 1 or 3, but sometimes up to 14 needles are held by the needle jigs. The number of needles used depends upon the tattoo pattern. The inside diameter of the needle jig is larger than that of the bunch of needles used so that the needles be moved back and forth into the jig easily by the driving vibrator. Usually, the needles retract in the jig.

The tattooing procedure we saw when we visited a tattoo shop in Christchurch may be divided into three steps. Firstly the artist, John, shaved the hair and cleaned the skin with methylated spirits where the tattoo was to be done. Then he drew a tattoo pattern on the skin with indelible pencil. Finally, the tattooing machine was used. John dipped the tip of the jig in dye which is mixed with water and pigment powder. The tip of the needles vibrate back and forth along the line of the tattoo pattern at an small angle to the surface. When the needles go down the needles penetrate the skin and holes are made. When the needles come back up the tattoo dye goes in to the skin. Methylated spirits and tissue paper are used in this step, to absorb the bleeding and remove surplus tattoo dyes. For much of the following information, I am indebted to Ms Carol Miles. She has a MSc in physics and was a staff member of this department for many years. She has a background in optics and dyes.

Carol Miles has had professional tattoos for forty years, and owns professional tattooing equipment and a range of dyes. She told us that the sensation of tattooing was like sunburn. She also said that the tattoo was heavily coloured after tattooing. However, the tattoo's colour became lighter as new skin was formed, because part of the tattoo pigment peeled off with the crust and part was taken away by the body's defences. The tattoo pigment fades and spreads out with time. Black tattoos, after 60 to 70 years become light blue. Coloured tattoos, such as yellow, red and blue disappear 50 years after tattooing. Tattoos fade faster perhaps in 2 to 5 years on the knuckles and wrists where skin is flexed. Over the years sharp lines of a tattoo become wider.

Carbon black is used for black and blue tattoos. She also told us of a typical method for obtaining coloured tattoo dyes. Organic dyes are dissolved in water, absorbed on aluminium hydroxide ($Al(OH)_3$), forming an aluminium hydroxide hydrate ($Al(OH)_2.xH_2O$) which is then heated and ground to powder. The organic dye adheres to or is trapped inside the Al_2O_3 granules.

The principal pigments used for present professional tattoos are commercial dyes. Coloured professional tattoo dyes contain a variety of metals, such as mercury, iron, aluminium, cobalt, copper, titanium, chromium, lead, and magnesium. The aim is both to make tattoo colours vivid and permanent, as reported in many places (Loewenthal 1960, Silberberg and Leider 1970, Agris 1977, Slater and Durrant 1984). Spaulding & Rogers MFG., Inc. which has 37 years history in the tattoo supply business, specify that thier commercial black ink contains 8% carbon, 2% additives and 1% other substances.

Ms Miles is sure that the majority of modern dyes are organic, but several medical references reported that they found various metals in the coloured tattoo skin. Tattooists have been rather reticent to provide details. We do not know the exact constituents that used in tattooing and presume that they are organo-metallic compounds. It would be worth doing chemical assays on a sample of modern commercial dyes. We need to know the thermal stability of dyes to fully understand the mechanism of selective photothermolysis tattoo removal.

Carol Miles mentioned that the size of tattoo pigment particles is particularly important. Tattoo dyes must be ground to a uniform size because, while small tattoo pigment particles will flow away in the body and large ones will be rejected, middle sized ones of 1 to 5 μm can stay in the cells. Taylor *et al* (1990) reported that the pigment particles of sizes varying from 2 to 400 nm. We note that the pigment particles form clusters of typically 1 to 20 μm in our histological study. The pigment clusters are in suspension, and it would seem that pigment clusters are surrounded by membranes (usually fibroblasts) and retained in the skin. Smaller clusters are flushed out through the lymphatic system, and larger clusters are rejected in the initial scabbing. Such a behaviour is consistent with the known behaviour of foreign matter in the lung (C Winterbourn 1989, private communication).

3.5 Amateur tattoos

Amateur tattoos are produced by a nonuniform depth penetration to varying levels of the epidermis, dermis, or subcutaneous tissue (Taylor *et al* 1990) by nonsterile or semisterile sharp objects such as needles, pens, and so forth. The pigmentation consequently varies greatly in location and concentration as well as in particle size. This variation tends to produce less distinct, blurred lines. Amateur tattoos tend to be more crude and simplistic than the often elegant and very artistic designs of the professional tattoo artist. Amateur tattoo pigments are usually obtained from India ink, pencil lead, lamp black, eyeshadow, shoe polish or carbon particles from burning charcoal or other substances(Agris 1977, Apfelberg *et al* 1980).

3.6 Tattoo pigment distribution

Tattoo pigment distribution in the skin has been studied by electron microscope. Three specimens were provided by Mr. Walker. It is shown microscopically that tattoo pigment particles accumulate into big or small diverse clumps that are membrane-bound. We can see the shape of the granules on the edge of the cluster in Figure 3.3. However, it is hard to see the single tattoo granules in suspension in tissue in Figure 3.3, or in other sections. Tattoo pigment granules are sealed by collagen walled

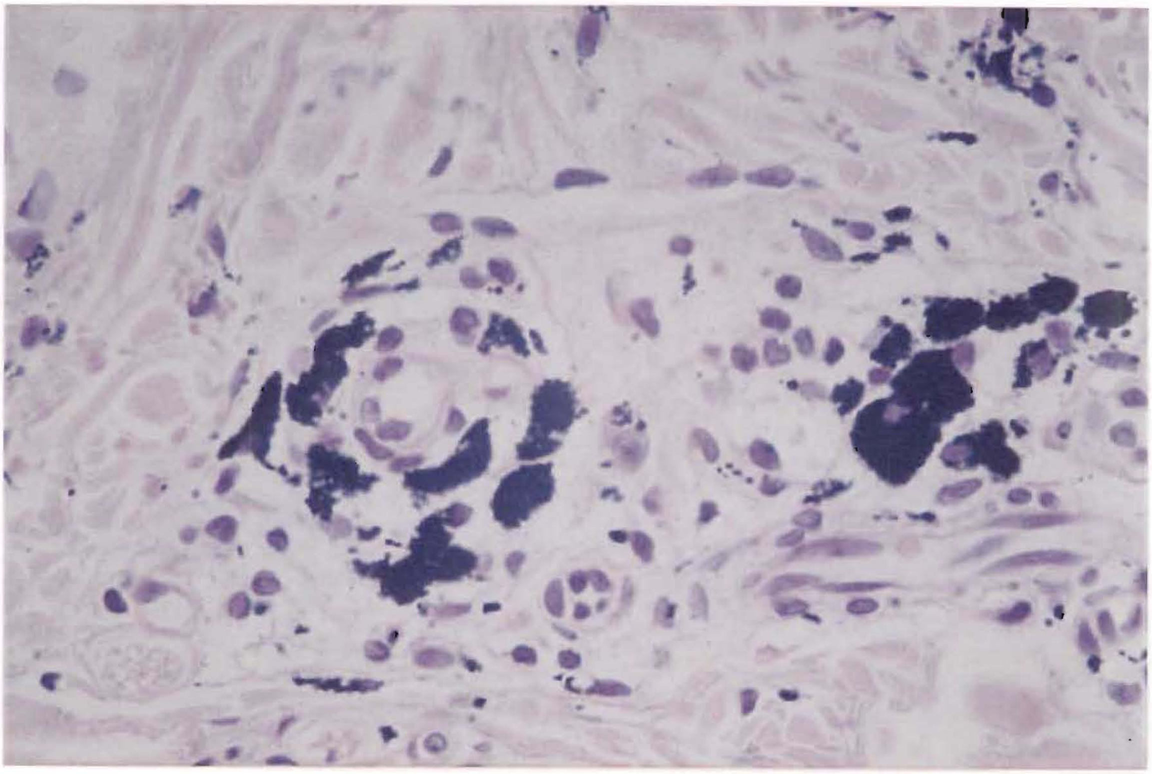


Figure 3.3 View of tattoo pigment cluster (400×)

Table **3.1** Distribution of pigment cluster in size in average

Cluster height (h)	percentage
15-30 μm	20%
5-15μm	70%
1-5μm	10%

clusters, mostly in fibroblasts which surround blood vessels.

In some tattoos, the clusters of the pigment are scattered throughout the epidermis and dermis. Specimen 1 shows skin with a pigmented basal epidermal layer. In the dermis there is patchy accumulation of dark pigment clusters. The sizes of the clusters vary from 1 to 30 μm, the depth of distribution varies greatly, from 0.2 to 1.05 mm (see Figure 3.4). There are heavier accumulations of pigment in histiocytes aggregated around blood vessels.

Specimen 2 shows dark pigment clusters (see Figure 3.5). The clusters have aggregated in the upper and mid dermis, the depth of clusters in the skin is from 0.15 to 0.5 mm and the size of the clusters range from 1 to 20 μm. Specimen 3 shows accumulations of dark pigment in histiocytes in the upper and mid dermis (see Figure

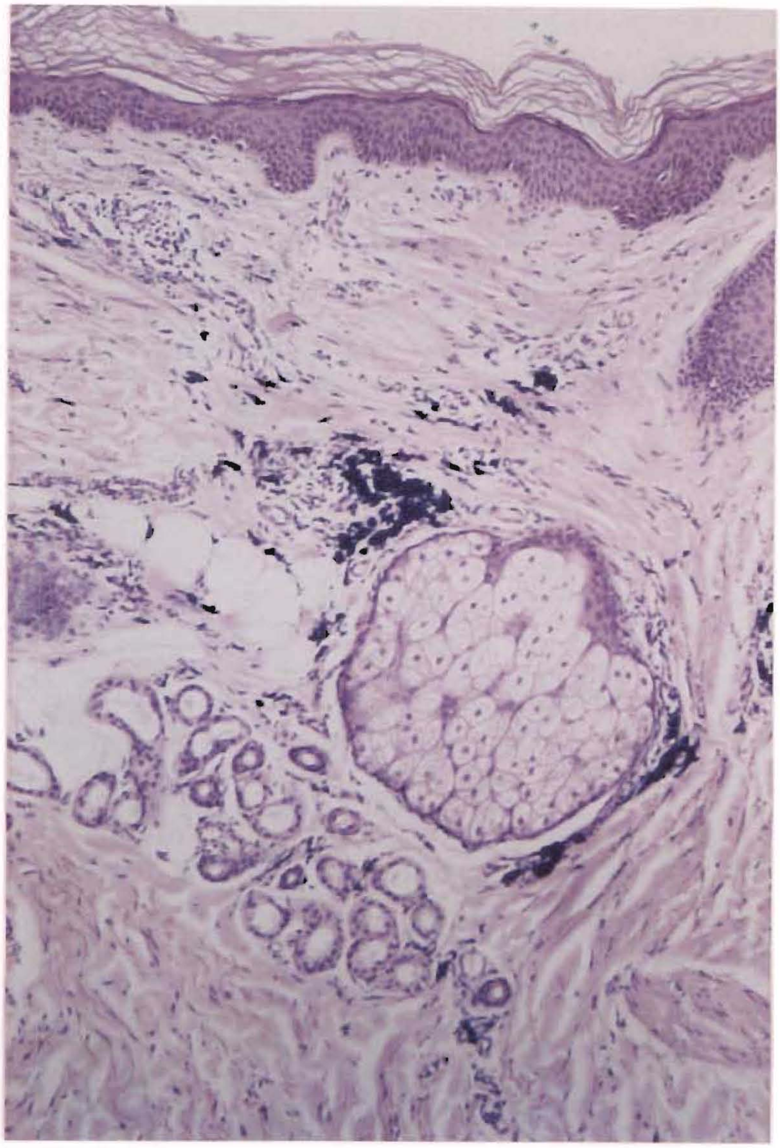


Figure 3.4 Diffuse tattoo pigments in skin (63×)

3.6). The size of pigment clusters varies from 1 to 20 μm and the depth of the pigment clusters from 0.1 to 0.6 mm.

From the above analysis, we find out that there are great variations in depth from 0.1 mm to 1 mm for tattoo pigment clusters. The size of pigment clusters varies from 1μm to 30μm. The size of most of the clusters is between 5μm and 15μm. Our measured size distribution of pigment clusters is shown in Table 3.1.

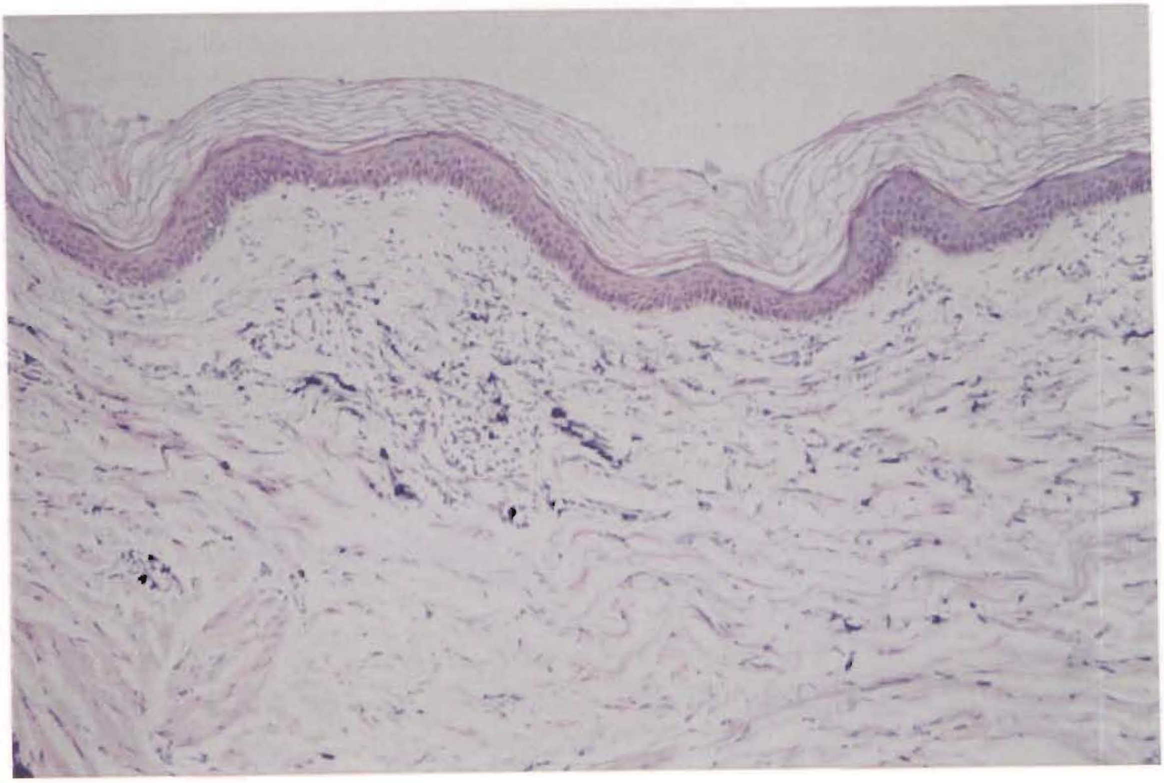


Figure 3.5 Tattoo pigments in the skin (63×)

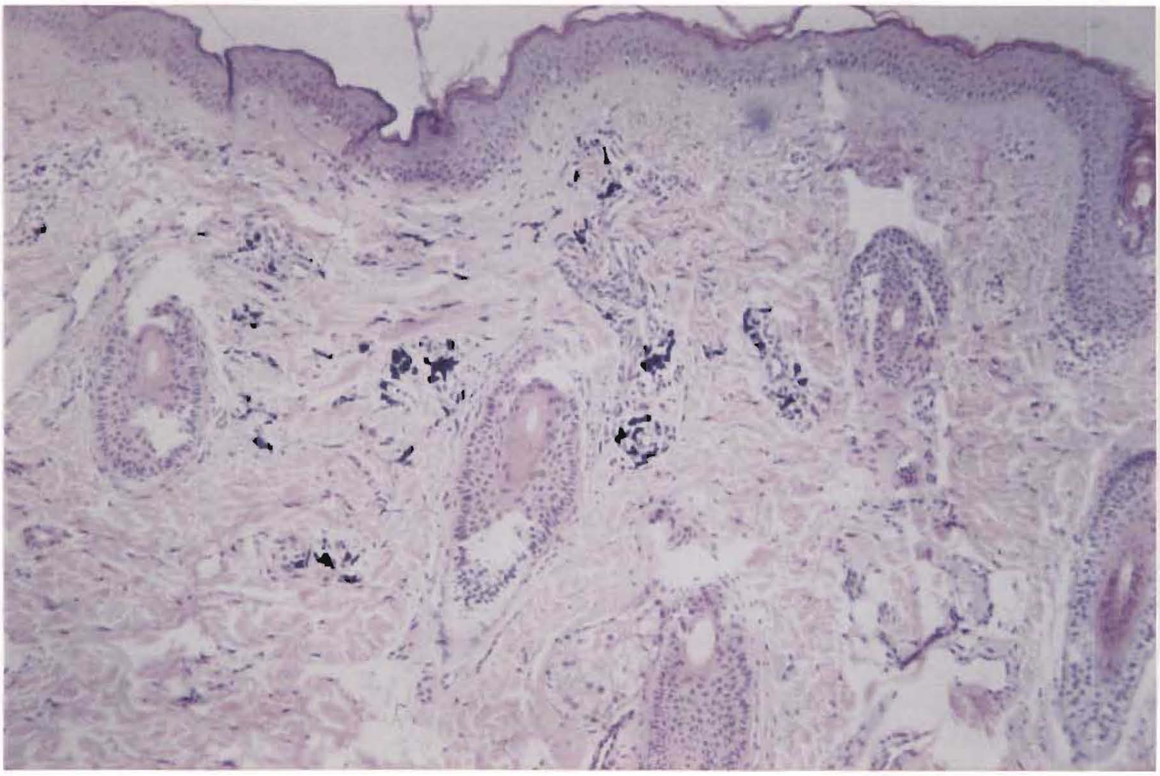


Figure 3.6 Distribution of tattoo pigment clusters (63×)

CHAPTER 4

Mechanisms

In this chapter we will first describe the selective photothermolysis concept and analyze the necessary conditions for applying this principle. Then we will discuss the mechanism of the Q-switched ruby laser when used for the treatment of the tattoos. We postulate that this laser works by selective photothermolysis, and thus propose that repeat treatments are necessary for this reason. Finally, we will calculate the thermal relaxation time so that we can determine theoretically an upper limit for the duration of the pulse of radiation, and a minimum energy intensity necessary to break up tattoo pigment clusters by selective photothermolysis.

4.1 Selective photothermolysis concept

'Selective photothermolysis' refers to the concept of producing specific, thermally mediated injury to optical targets in the various tissues, using brief and selectively absorbed radiation. The desired targets may be pigmented skin structures and pigment-containing cells. Tissues between targeted structures, including overlying or immediately neighbouring cells, are spared, reducing widespread destruction and nonspecific fibrosis. The selective photothermolysis mechanism may be particularly useful in highly scattering tissues.

The technique of selective photothermolysis relies on selective absorption of a brief radiation pulse to generate heat in inside the target volume, so that damaging temperatures rises are confined to the target, thus avoiding injury to surrounding tissue. This principle of localising the thermal damage to specific targets in the radiation field has been successfully employed to destroy the abnormally ectatic blood vessels in port wine stains and skin telangiectases. More recently, attention has been directed at the cutaneous endogenous chromophore, melanin, especially in the brown marks common in asian skin or 'age-sports' in caucasian skin.

The effectiveness of selective photothermolysis depends upon the ability to confine the temperature rise specifically to the target. There are three conditions which have to be met when this technique is applied. The first condition is a sufficient spectral match between the radiation and the targets. That is, the targets must have a greater optical absorption at some wavelength than their surrounding tissues. This requirement can be met either by choosing an appropriate spectral region of radiation or by using a staining or dye-labeling technique.

The second condition is that the time of the energy delivery must be shorter than that of significant thermal conduction. The light exposure duration dictates the extent of the local confinement of the heating effect produced. During the light exposure, radiation energy is converted into heat within each target in the exposure field. Accompanying this heating the targets begin to transfer the heat to their cooler surroundings mainly by thermal conduction, but this process takes some time which depends the exposure duration. In order to obtain rapid heating of the targets and to generate a irreversible effect on them, the exposure time must be of the order of, or less than the thermal relaxation time of the targets discussed in detail in section 4.4.1.

The third condition is that a sufficient energy density is necessary to generate the thermal effects required. These effects include coagulation necrosis[1] and vaporisation[2] of tissues.

4.2 Postulated mechanism for removal of tattoos by Q-switched ruby laser

Q-switched ruby lasers are able to remove tattoos completely without the usual risks of textural change or scarring. The reason for that is that output parameters of pulse duration, energy intensity and wavelength from this laser satisfy the conditions for the selective photothermolysis technique. The radiation specifically targets tattoo pigment in the skin, and the other parameters are such that any damage to the surrounding tissue is repaired.

First, the deep red light from the Q-switched ruby laser, having a wavelength of 694.3 nm, is beyond the main absorption peak for hemoglobin and less absorbed by melanin in the epidermis than by tattoo pigments. Although there is some reflection on the skin surface and some scattering in the skin, some of the light penetrates the translucent epidermis and dermis, and is absorbed by carbon pigments.

Second, Q-switched ruby lasers produce very short pulses of radiation with high intensity. The pulse duration of 30 to 40 ns is much shorter than the thermal relaxation time of even the smallest pigment clusters (see Table 4.2). Hence the temperature

[1] Normal skin temperature is about 35°C and if soft tissue is heated from this level to above 60°C the process of coagulation begins.

[2] When tissue is heated to above 100°C the process of vaporisation occurs

rise of the cluster will be much higher than that of the surrounding tissue, resulting in little damage to this tissue.

Because of the above factors, most of the radiation from the Q-switched ruby laser is absorbed by tattoo pigments. Absorption and radiationless de-excitation convert radiant energy into heat within each tattoo cell in the exposed area. Large temperature rises are induced in the vicinity of the pigment clusters. The cell fluid will boil when tissue is heated to above 100°C, since the body cells may be considered to be mostly water under normal atmospheric pressure. The conversion of water into steam represents a thousand-fold expansion and leads to an explosive interaction which breaks up the tattoo pigment containers.

The pigment particles are then released from the containers. This effect promotes an accumulation of macrophages [3] in the injured area. Fragments of the containers and tattoo pigment granules are removed through the process of phagocytosis. Macrophage activity transports the scattered pigment particles away. Tattoos gradually fade. Usually this process takes two to three weeks.

However, the Q-switched ruby laser cannot remove coloured tattoos other than blue and black because the ruby laser light has a wavelength of 694.3 nm. The absorption spectrum of several dyes are shown in Figures 5.5 and 5.6. There is little absorption at 694.3 nm for orange, gold yellow, yellow, brown and violet tattoo pigment, but black, white and green tattoo dyes have a high absorption at 694.3 nm.

4.3 Multiple treatments explanation

A number of repeat treatments are required to remove tattoos completely in most cases. Re-treatments necessary for amateur tattoos vary between four and six. For professional tattoos, six or seven, even as many as twelve treatments may be necessary to obtain optimal results. However, on occasions only one or two treatments has been needed to remove a tattoo completely (White 1992a, b) .

We propose that the number of repeat treatments necessary depends on distribution in density and depth of the tattoo pigment clusters. Histological studies detailed in Chapter 3, show that the distribution of tattoo pigment clusters range in depth from 0.1 to 1 mm below the skin surface. Blue and black tattoo pigments absorb 100% of incident light on them, so it is probable that little light penetrates beneath the upper cells of the tattoo. This results in only the upper of tattoo pigment cells responding on any one exposure. The tattoo pigment within the skin can be removed layer by layer by this selective photothermolysis mechanism. The higher the density of pigment clusters, the higher number of treatments. Professional tattoos need more

[3]Macrophages are the white blood cells that surround and carry away foreign particles or dead cells.

treatments than amateur tattoos, because the pigment clusters of professional tattoos are generally of a higher density.

4.4 Calculations

4.4.1 Thermal relaxation time

The duration of the pulse of radiation is a very important treatment parameter for selective photothermolysis. It determines the illumination time. The illumination time determines the extent of conduction of delivered energy from the target. To minimum conduction losses, the illumination time must be less than the thermal relaxation time (τ) of the target (Kuban *et al* 1992). The thermal relaxation time of the target is an estimate of the time required for the target to release a certain fraction of the heat within it. In the case of a target in the skin, this time is normally defined as: the time it takes for the central temperature to fall to half way between its peak temperature and the temperature of the surrounding structures (Pickering *et al* 1989b). We apply this definition to tattoo pigment clusters in the skin to estimate a maximum optimal illumination time.

To calculate thermal relaxation time we begin with the fundamental law of heat conduction

$$\frac{dQ}{dt} = -\eta \vec{A} \cdot \nabla T \tag{4.1}$$

where

- Q is the heat within the structure,
- t is the time,
- η is the thermal conductivity,
- A is the area through which the heat is conducted,
- ∇T is the temperature gradient.

In the case of tattoo pigment clusters, we make the assumption that the cluster is a sphere of radius r, and that the normal tissue temperature, T_o is 35°C.

Immediately after exposure, the average temperature of the tattoo pigment clusters has increased by ΔT ($\Delta T = T - T_0$). The excess heat energy within the cluster is given by

$$Q = \frac{4}{3}\pi r^3 \rho C_v \Delta T. \tag{4.2}$$

If we assume that the temperature throughout the cluster is uniform and as simplification take the temperature gradient at the surface of the cluster as $\frac{\Delta T}{r}$ approximately then substituting in equation 4.1, we have

$$\frac{dQ}{dt} = -4\eta\pi r^2 \frac{\Delta T}{r}. \tag{4.3}$$

The tissue parameters C_v, ρ and η are presented in Table 4.1. combining equations (4.3) and (4.2), we obtain

$$\frac{d(\Delta T)}{\Delta T} = -\frac{3\eta}{C_v \rho r^2} dt. \tag{4.4}$$

Integrating equation 4.4, we have

$$T = T_o + (\Delta T)_o e^{-\frac{3\eta}{c_v \rho r^2} t} \tag{4.5}$$

where $(\Delta T)_o$ is the initial increase in temperature. Then, letting $\tau_o = \frac{C_v \rho r^2}{3\eta}$,

$$T = T_o + (\Delta T)_o e^{-\frac{t}{\tau_o}}. \tag{4.6}$$

According to our definition of thermal relaxation time, we have for a 50% drop in the relative peak temperature a thermal relaxation time(τ) of

$$\tau = \tau_o \ln 2. \tag{4.7}$$

The ultimate goal of defining the 'optimal' parameters will be specifically to destroy only tattoo pigment cells in the cutaneous tissue. If the illumination time is much longer than the thermal relaxation time of the target then during its heating a considerable amount of heat will be conducted away and the surrounding structures can be expected to be heated because the tattoo pigment cells are not thermally isolated.

The thermal relaxation time depends upon the size of the pigment cluster and values for varying radius of tattoo pigment clusters are shown in Table 4.2. We found from histological studies that most tattoo pigment clusters are around 5 to 15 μm in diameter and therefore pulse duration ought to be less than 100 μs.

Table 4.1 Tissue parameters (Pickering *et al* 1989a)

Parameters	Values
Density(ρ)	10^3 kg m^{-3}
Heat capacity(C_v)	3.5$\times$ 10^3 J kg^{-1}°C^{-1}
Thermal conductivity(η)	0.62 W m^{-1} °C^{-1}

Table 4.2 Thermal relaxation time

Pigment cluster size (radius)	Thermal relaxation time(τ)
1 μm	1 μs
2 μm	5 μs
5 μm	30 μs
10 μm	130 μs
15 μm	300 μs
20 μm	500 μs

4.4.2 Energy intensity

According to the mechanism of selective photothermolysis removal of tattoos, the energy intensity must be sufficient to heat tattoo pigment cells to a temperature that results in tattoo pigment cells breaking up. Therefore the exposure dose is also a very important treatment parameter. However, it is a complex question to estimate accurately the exposure dose required on the skin surface. The tattoo pigment cells are not isolated, they are suspended in the tissue and cannot be exposed directly. It is also unknow as to whether it is sufficient to denature the protecctive container (70°C) or necessary to rupture the cells explosively (100°C).

There are loss of incident energy before the light reaches the tattoo pigment cells due to the optical properties of human skin. Firstly, there is a reflection loss on the skin surface. At near-normal incidence, a small fraction of incident radiation is reflected due to the change in refractive index from air ($n_i = 1.0$) to stratum corneum ($n_t = 1.55$) (Scheuplein 1964). This regular reflectance of an incident beam from normal skin is betweeen about 4% and 7% over the entire spectrum from 750 nm to 3000 nm for both white and black skin.

Output light from the xenon flash lamp radiates in all directions. In this case, reflection is increased. Fresnel's formula predicts about 10% of incident light is reflected from the skin surface. The reflection results because the surface of the stratum corneum is not smooth and planar: (1) the regular reflectance from skin is not specular and (2) a beam of incident radiation in all directions, passing through this surface and into skin, is refracted and therefore is made somewhat more diffuse by this rough surface. These effects are similar to those which make ground glass translucent, compared with the transparency of polished glass.

Secondly, the incident radiation of 90%, not returned by regular reflectance, may be absorbed or scattered in the skin before reaching tattoo pigment cells. In the epidermis, melanin is the major absorber of radiation . The absorption of melanin depends upon the wavelength, having a high absorption peak at less than 275 nm (Anderson and Parrish 1981). There is also scattering in the skin, resulting from inhomogeneities in a medium refractive index, corresponding to physical inhomogeneities. For particles with dimensions on the same order as the wavelength, scattering is much stronger. In particular, scattering by collagen fibers appears to be of major importance in determining the penetration of optical radiation within the dermis (Anderson and Parrish in 1980).

These two factors taken together essentially determine the penetration of radiation before reaching tattoo pigment cells. A total incident radiation loss of 30% to 50% in these two processes was estimated by considering the treatment of port wine stains (Pickering *et al* 1989a).

In our experiment, we found that there is more loss in the epidermis during the exposure, which will be discussed in chapter 7.

In our calculation, we assume that the tattoo pigment cells are exposed directly and do not consider various losses on the skin surface and in the skin. We assume the tattoo pigment cluster to be a disk with thickness h and cross sectional area S. To heat such a cell to $100°C$, the energy required is

$$Q = C_v \rho S h \Delta T \tag{4.8}$$

where the energy intensity D=Q/S is

$$D = C_v \rho h \Delta T \tag{4.9}$$

Table 4.3 Required energy intensity when the tattoo pigment cluster is directly exposed

Pigment cluster thickness (h)	Energy intensity
2 μm	0.07 Jcm^{-2}
5 μm	0.17 Jcm^{-2}
10 μm	0.35 Jcm^{-2}
15 μm	0.53 Jcm^{-2}
20 μm	0.70 Jcm^{-2}

Table 4.3 gives minimum energy intensity which is required to heat tattoo pigment clusters to 100°C when exposed directly. If we take into account energy losses on the skin surface and in the skin, the exposure dose used on the skin surface should be higher than above results suggest. Reid *et al* reported however that energy intensity of rang 4 to 8 J cm^{-2} are required for the Q-switched ruby laser treatment.

CHAPTER 5

Spectrum matching

In this chapter we will discuss particularly the spectrum match between the xenon flashlamp's radiation and the absorption of the tattoo dyes. First, we will present the output spectrum from the xenon flashlamp and the measurements we have made of the tattoo dyes absorption and analyze the spectrum match in the visible region.

Secondly, we discuss exposure limits to the exposure of the skin to ultraviolet because the radiation of the xenon flashlamp contains UV. We have measured the transmission spectrum of three kinds of UV glass filter and that ordinary window glass provides sufficient absorption to satisfy the standard for exposure of the skin to UV radiation. As well, it also has a high transmission rate in the visible region.

5.1 Radiation of xenon flashlamp

Spectral output from a xenon flashlamp covers a wide range of wavelength. This extends from ultraviolet to infrared. The spectral output of a xenon flashlamp depends to a great extent on the discharge current density. For instance, at low current density the spectral output is heavily weighted toward the visible and infrared. As current is increased, the output spectrum shifts toward the blue and ultraviolet. This occurrence is illustrated in Figure 5.1 which shows spectral curves for the Model-457A high current intensity, micropulse system. Table 5.1 shows the spectral distribution at various current densities. Spectral output is also affected by the envelope material of the flashlamp. Natural fused silica is often used as a envelope material. Its transmission spectrum ranges from 175 nm to 5000 nm.

Wavelength (nm)	Spectrum distribution (%)		
	400-1500(A cm^{-2})	2000-5500 (A cm^{-2})	6000-14000(A cm^{-2})
200-300	5	8	20
300-400	11	16	15
400-500	14	17	14
500-600	13	14	14
600-700	10	10	7
800-900	16	11	8
900-1000	15	9	7
1000-1100	5	4	3

Table 5.1 Spectrum distribution at various current densities. This table gives the spectrum distribution of three ranges of current densities (Xenon Corporation, 1992).

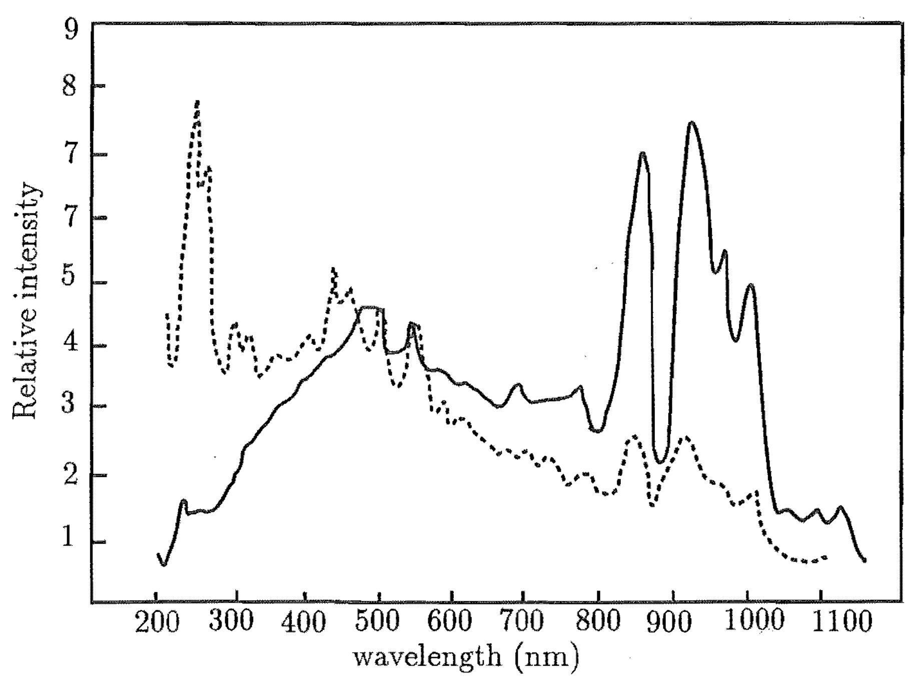


Figure 5.1 Xenon flashlamp output spectrum of the Model-457A high intensity micropulse system. The dotted line corresponds to a high current density and the solid line corresponds to a low current density (Xenon Corporation, 1992).

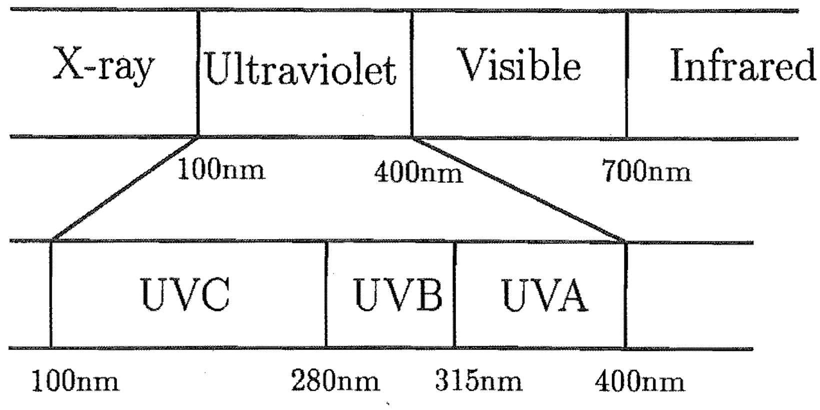


Figure 5.2 The ultraviolet spectrum is divided into three regions, UVA, UVB and UVC.

5.2 Exposure limits to UV

Because the flashlamp output spectrum includes ultraviolet, it is important to understand ultraviolet exposure limits to prevent hazard to the treated skin.

Exposure to ultraviolet radiation can produce harmful effects in the skin. These include the effects of acute and chronic. The former include erythema, oedema and blistering. Most acute biological effects are initiated by wavelengths less than 315 nm. The wavelength range 180-315 nm is often referred to as the actinic region. Chronic effects of exposure to ultraviolet radiation include premature skin aging and skin cancer. As with acute effects, the most dangerous wavelengths appear to be those below 315 nm.

We investigated the exposure limits for ultraviolet carefully. There is no New Zealand standard or legislation prescribing maximum permissible exposures to ultraviolet radiation. However, we obtained a document 'Occupational Standard for Exposure to Ultraviolet Radiation' from the National Radiation Laboratory in Christchurch. This document was approved at the 108th session of the National Health and Medical Research Council in Canberra in 1989 and was published by the Australian Radiation Laboratory on behalf of the National Health and Medical Research Council.

This standard is for both general and occupational exposure to ultraviolet radiation incident upon the skin or eye. The exposure limits are considered separately for the three regions of ultraviolet. The international commission on illumination has divided the wavelengths between 400 nm to 100 nm into three regions. Figure 5.2 shows the three regions UVA (315-400 nm), UVB (280-315 nm) and UVC (280-180 nm).

For the wavelengths of the three regions of UVA, UVB and UVC the exposure limits are given in the National Health and Medical Research Council (National Health and Medical Research Council, 1989). For example, for the wavelengths 315 nm and

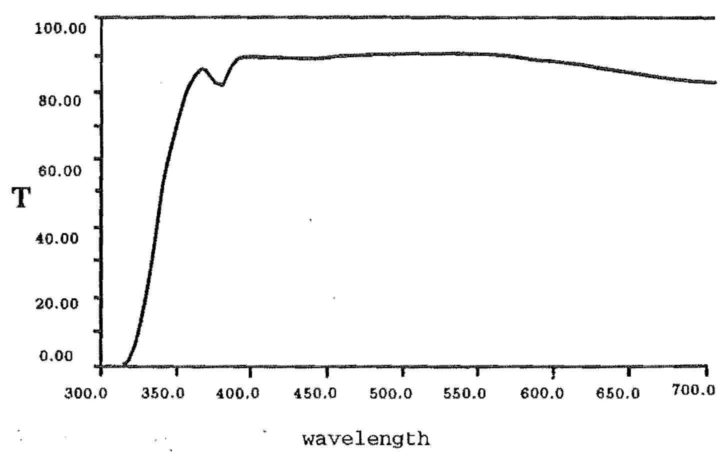
400 nm UVA the total radiant exposure incident upon unprotected skin should not exceed $1.0\,\mathrm{J\,cm^{-2}}$ and $100\ \mathrm{J\,cm^{-2}}$ respectively within an 8 hour period. However, for the wavelengths 305 nm and 270 nm the total radiant exposure incident upon unprotected skin should not exceed $50 \times 10^{-3}\ \mathrm{J\,cm^{-2}}$ and $3 \times 10^{-3}\ \mathrm{J\,cm^{-2}}$ in a similar period. The exposure limits for UV are very different for regions of UVA, UVB and UVC. Generally the exposure limits for the regions of UVB and UVC are much lower than for UVA.

When the flashlamp operates at high current density, an UV filter is needed in order to prevent hazard to the treatment area. We measured the transmission spectrum of three kinds of glass by a UV/Vis spectrometer (Model Lambds 2) in chemistry. The first was ordinary glass of 1 mm and 5 mm thickness. This glass filters out the two regions UVB and UVC while about 94% of the visible spectrum passes through. The transmission spectrum curves of ordinary glass are shown in Figures 3(a) and 3(b). The second type of UV filter glass was a cesium doped fused silica jacket supplied by the Xenon Corporation to cover the flashlamp. There is about 30% penetration in the spectrum range of 220 nm to 280 nm and there are two valleys at 220 nm and 320 nm in the transmission curve shown in Figure 5.4. Thirdly, we used UV filter glass supplied by AG Thompson. This filter cuts off the entire region of UVA and UVB and the infrared. However, visible transmittance is lower than with the other glasses (see Figure 5.4). By comparing the three kinds of glass, we think that 5 mm of ordinary glass as a ultraviolet filter in our application is sufficient.

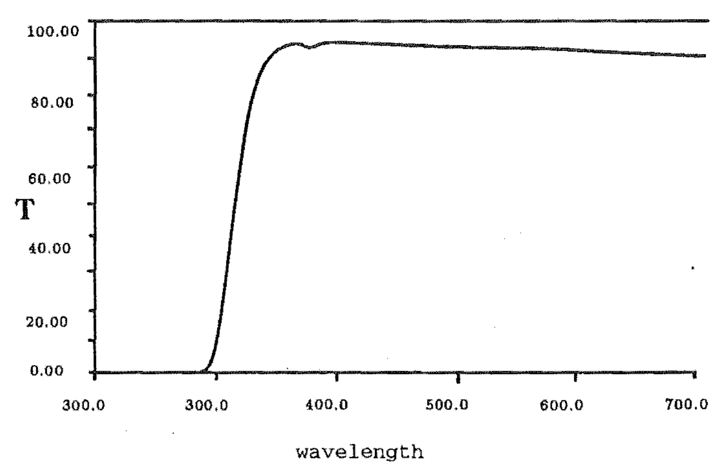
5.3 Spectrum match between tattoo dyes and flashlamp radiation

We obtained eight colour tattoo dyes manufactured in 1965 by Fazandie Sperrle Inc.. The colours are violet, green, brown, yellow, gold yellow, orange, white and black. Their absorption spectra in the visible region were measured by a UV/Vis spectrometer (Model lambda 2) in chemistry. The samples were prepared by smearing the dry tattoo powder on the paper and measurement was carried by reflection. Black and white tattoo dyes have a uniform absorption over a range of measurement (350 nm - 750 nm).

The relative absorption intensity of the remaining six tattoo dyes (violet, green, brown, yellow, gold yellow and orange) as a function of wavelength are shown in Figures 5.5 and 5.6. These curves show the position of their maximum absorption wavelengths and the range of absorption for each tattoo dye. It is evident that the absorption spectrum range of the six tattoo dyes covers the entire visible region from 400 nm to 700 nm. It indicates that over much of the visible spectrum there is a good match between the radiation of the xenon flashlamp and the absorption region



(a) 5 mm glass thickness



(b) 1 mm glass thickness

Figure 5.3 Ordinary glass transmission curves.

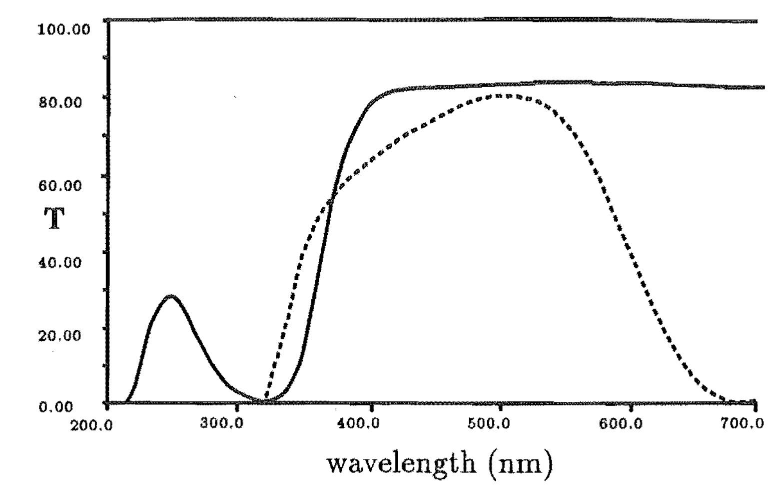


Figure 5.4 UV filter transmission curves. The dotted line corresponds to a 1 mm Band pass filter transmission curve. The solid line corresponds to a 1.5 mm cesium doped fused silica transmission curve.

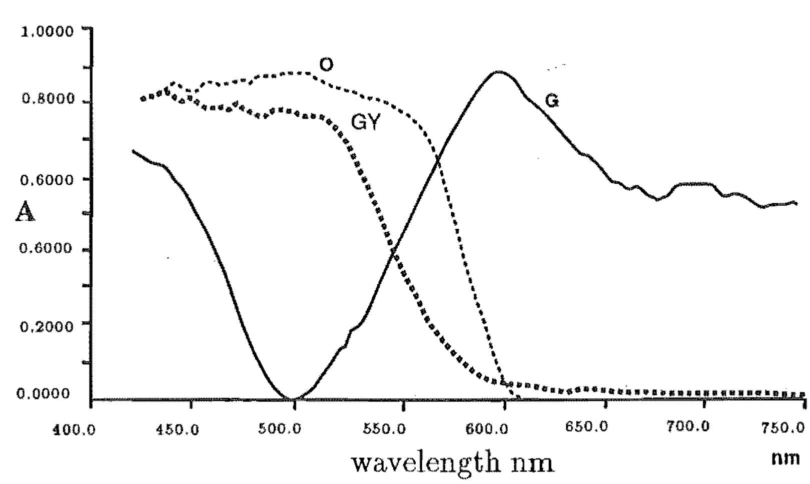


Figure 5.5 Tattoo dyes relative absorption intensity. Curves O, G and GY represent orange, green and gold yellow tattoo dyes respectively.

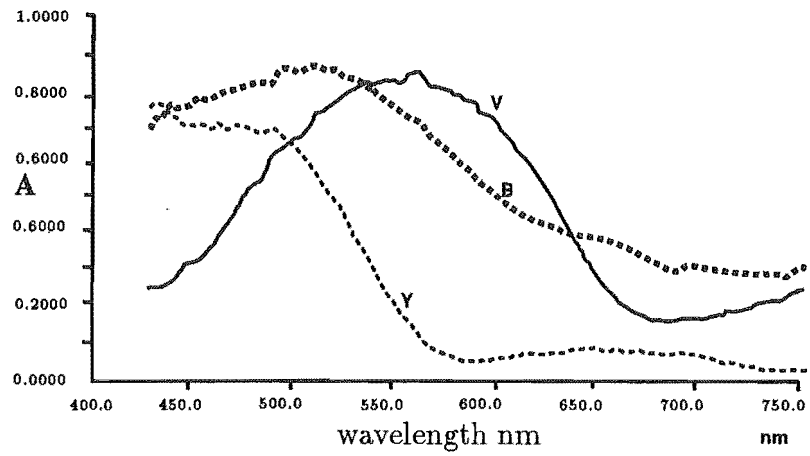


Figure 5.6 Tattoo dyes relative absorption intensity. Curves V, Y and B represent violet, yellow and brown tattoo dyes respectively

of tattoo dyes. This, which may be one of important advantage for the removal of tattoos by xenon flashlamp, was experimentally verified. A flashlamp with output of 20 μs and 2.5 J was used on a volunteer's tattoo. The skin area had black and red tattooed area and normal skin. The experimental results showed the response in the black area was greater than that in the red tattoo, which was a little greater than for normal skin.

We also observed that there is no absorption peak for the six tattoo dyes in region of 650 nm to 700 nm. This result explains why Q-switched ruby lasers are not successful in removing most coloured tattoos.

CHAPTER 6

Theory of the xenon flashlamp

It is very important to optimise the design of the flashlamp bore, length and fill pressure to match its electric circuit, so that the system obtains the highest possible radiation efficiency. The flashlamp will also have a proper lifetime, and its output spectrum will satisfy the treatment requirements. Hence it is necessary to study the characteristics of the flashlamp itself — its output and electrical circuit are of particular interest for this purpose.

In this chapter, we will mainly discuss characteristics of linear flashlamps. First, we will describe what a xenon flashlamp is and its idealized electrical characteristics. Then we will present an analysis of the discharge circuit behaviour of a flashlamp, such as the relationship of voltage and current for the flashlamp and the peak current through the flashlamp. As well, we will discuss the importance of the flashlamp operating at critical damping and how to design an electrical circuit to achieve this. We also discuss several trigger circuits including over-voltage, external, series and simmer trigger. We will also analyse the factors which affect flashlamp lifetime and efficiency.

6.1 Characteristics of the xenon flashlamp

Xenon flashlamps are gas discharge tubes, filled with the inert gas, xenon, designed to produce both pulsed and continuous radiation. Xenon lamps are similar to all other arc lamps in that optical radiation is produced by passing an electrical current through a gas. A continuum spectra is produced when sufficient energy is transferred to the xenon gas atoms to cause excitation and ionisation. Xenon is used in most flashlamps, since it is the most efficient of the inert gases at converting electrical energy to optical energy. For pulsed operation, the current is supplied by a charged capacitor capable of discharging the appropriate energy in the appropriate time. Depending on the values of the capacitor and other circuit components, pulse widths from under 1 microsecond to over 50 milliseconds and energies from millijoules to kilojoules can be obtained for xenon flashlamps.

The characteristic of producing energy in pulses of extremely high peak values and very short duration is a great advantage. A further advantage is that the output spectrum is broadband. However, specific regions of the spectrum can be emphasized by controlling the current through and the filling pressure of the flashlamp. These make them universally used for lasers, phototypesetting, chemical analyses, medical purposes etc.

Xenon flashlamps are available in many sizes and shapes including linear, bulb, helical and U-shaped and so on. But while there are many shapes of flashlamps, there are only two distinct basic types, linear and bulb.

The bulb type flashlamp is constructed from a small glass bulb. Bulb type flashlamps differ from linear flashlamps in that the arc is un-confined. The arc is formed between two electrodes mounted near the centre of the bulb. There are between one and five trigger probes, depending on the arc length and the space between the electrodes. This has the effect of applying a trigger voltage gradient across the probes. The trigger streamer strikes first from the cathode to the number 1 probe, then the segment from probe number 1 to number 2 is filled in, and so on until a complete trigger streamer is formed from the cathode to the anode. At this point, a low resistance path is formed, then the main capacitor dumps its stored energy into an arc following exactly the same path as the trigger streamer. This guide for the arc configuration results in an extremely stable source. Since the plasma does not contact the bulb wall, very long lifetimes can be obtained. Standard arc lengths available are 0.15, 0.30 and 0.80 cm. The combination of an un-confined arc and a short arc length results in very low arc impedance, therefore pulse duration are very short, typically between 0.7 and 15 microseconds. However, the output spectrum is very rich in the blue and ultraviolet and the maximum efficiency is about 20% for converting electrical energy to optical energy.

The linear type is of glass or quartz tubing construction with an electrode mounted at each end. The bore (inner diameter of the lamp) is completely filled with ionised gas when the lamp is flashed. Linear flashlamps can be made into a variety of shapes including helical, ring, U; electrically, however, there is no difference between two lamps that have same bore size, arc length (distance between electrodes), and fill pressure. Bore sizes from 0.1 to 1.9 cm and arc lengths from 2.5 to 120 cm are commonly available.

The driving circuit for a linear flashlamp is shown in Figure 6.1. This gives an useful illustration of how a flashlamp works. In the main discharge circuit an inductor, L, is placed in series with the flashlamp and capacitor, C. In the non-ionised state, a flashlamp has a high impedance; therefore all current from the power supply initially flows into the capacitor C. As the voltage across the capacitor is increased, a point

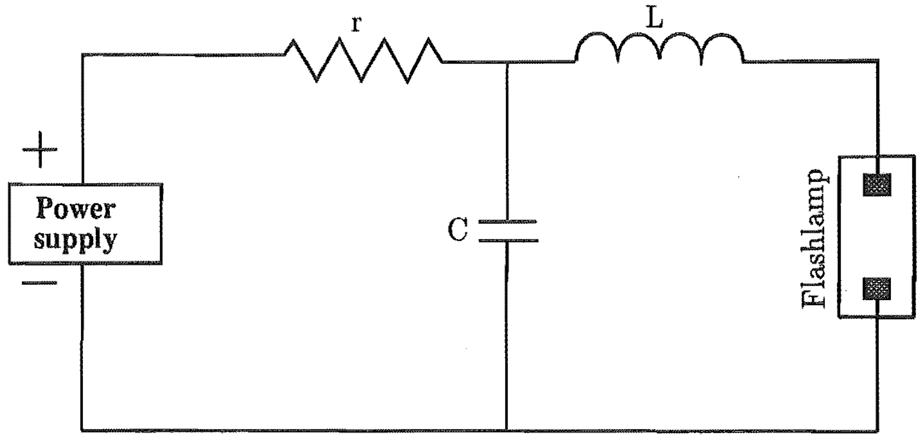


Figure 6.1 Basic discharge circuit

of charging voltage (V_o) is reached, called the breakdown voltage, where xenon atoms are ionised and the impedance of the flashlamp starts to drop. In a short period of time, enough xenon atoms are ionised so that a low impedance path is formed from anode to cathode and the current flows from the capacitor through the flashlamp. As this occurs, more xenon atoms are ionised; the arc impedance continues to drop and expands outward eventually filling the bore of the flashlamp. Once most of the energy stored in the capacitor is expended, the current through the flashlamp drops to such a low level that the gas de-ionised and stops conducting. At this point, the capacitor starts recharging.

6.2 Relationship of voltage and current for flashlamp

The main discharge circuit cannot be treated as a traditional RLC circuit, because the flashlamp does not behave as a linear resistor. Various relationships between voltage and current for flashlamps has been found. Goncz (1964) found the instantaneous flashlamp voltage (V) and current (i) to be related by:

$$V = K_o i^{0.5} \tag{6.1}$$

K_o, the flashlamp impedance, is totally determined by the flashlamp geometry and fill pressure. This parameter is calculated using the formula

$$K_0 = 1.28 \frac{l}{d} \left(\frac{P}{x} \right)^{\frac{1}{5}} \tag{6.2}$$

where

- l is arc length in mm,

- d is bore size in mm,
- P is fill pressure in torr, and
- x is a constant of 450 for xenon.

Goncz's work covered flashlamps with bore diameters varying from 0.13 to 2.8 cm and arc lengths of 0.6 to 30.5 cm. This finding was further confirmed by Dishington (1974) who found this relationship to be true for a 0.95 cm diameter flashlamp with a 7 cm arc length. This flashlamp was operated using the series triggering technique and had a maximum current density of about 2000 A cm^{-2}. While the relationship was found to be suitable for current densities from 300 to 10,000 A cm^{-2}, it was not applicable, however, for higher current densities. Subsequently, Marotta and Galvao (1978) found a relationship for a xenon filled flashlamp for the current density range from 4,500 to 35,000 A cm^{-2} which had the form

$$V = K_0 i^{0.85} \tag{6.3}$$

This work was done with a flashlamp with a 0.5 cm bore diameter and a 10 cm arc length operated using the simmered pre-pulse mode. Lue *et al* (1980) showed, both experimentally and theoretically, how the Goncz formula was applicable for current densities below 600 A cm^{-2} and Marotta's formula for current densities of more than 2000 A cm^{-2}. The general form of the voltage and current relationship has been derived by Rasiah *et al* (1991) who found different results from to those of Goncz and Marotta. However, the voltage–current relationship was also of the form

$$V = K_0 i^q \tag{6.4}$$

where the value of the power q was found to vary with the current densities. The power q is given by

$$q = 0.13 \ln(J) - 0.37 \tag{6.5}$$

where J is the current density in A cm^{-2}. This work was done with two flashlamps. One was a commercial model with a bore diameter of 0.6 cm and arc length of 10 cm filled to a pressure of 450 torr. This flashlamp was operated at input energies varying from 600 J to 1,000 J and a current pulse of about 2×10^{-3} s. The second flashlamp was a homemade non-sealed air filled linear flashlamp, which had a fixed length of 25 cm and a bore diameter of 0.9 cm. The flashlamp was filled with air and pumped down to a pressure of 0.6 Torr. It was operated at an input energy typically between 200 J and 500 J and a current pulse of 5×10^{-6} s.

The above relationships have assumed the voltage-current relationship in pulse discharge lamps to be constant throughout the discharge. This was shown to be true for a major portion of the flashlamp discharge by Dishington *et al* (1974) and Rasiah *et al* (1991). They showed that the assumption did not hold for the beginning of the discharge where the voltage–current relationship varied in a rather complicated manner. This change in the voltage–current relationship of the discharge was found to be drastic for input energies of less than 20 J, while higher input energies showed only slight variations. This may be due to the erratic behaviour of the discharge when the breakdown occurs within the flashlamp and this part of the flashlamp discharge is still not understood. The second part of the flashlamp discharge, on the other hand, is consistent and well described by the relationships detailed above.

6.3 Discharge character

In the main discharge circuit, the values of the inductance, L, the capacitance, C, the charge voltage, V and the parameters of the flashlamp are chosen carefully, so that the energy is transferred to the flashlamp in a critically damped state. Critical damping is important since it results in the most efficient transfer of energy from the capacitor to the flashlamp.

The design of a critically damped flashlamp circuit would be straightforward if it could be treated as a traditional RLC circuit. But, as remarked above, the flashlamp can not be treated as a linear resistor.

The differential equation for the single section flashlamp circuit of Figure 6.1 is

$$L\frac{di}{dt} + K_0|i|^{1/2} + \frac{1}{C}\int_0^t i dt' = V_0 \tag{6.6}$$

where V_0 is the initial voltage on the storage capacitor and t is the time. It should be noted that equation (6.1) is used, that is, a circuit with low current density is considered, and the driving circuit is assumed lossless.

With the following substitutions and normalisation.

- $Z_0 = \sqrt{L/C}$
- $I=(Z_0/V_0)i$
- $\mathrm{T}=\sqrt{LC}$
- $\tau = t/T$
- $\alpha=K_0/\sqrt{V_0 Z_0}$

Equation (6.6) can be rewritten as

$$\frac{dI}{d\tau} + \alpha|I|^{1/2} + \int_0^\tau I d\tau' = 1 \tag{6.7}$$

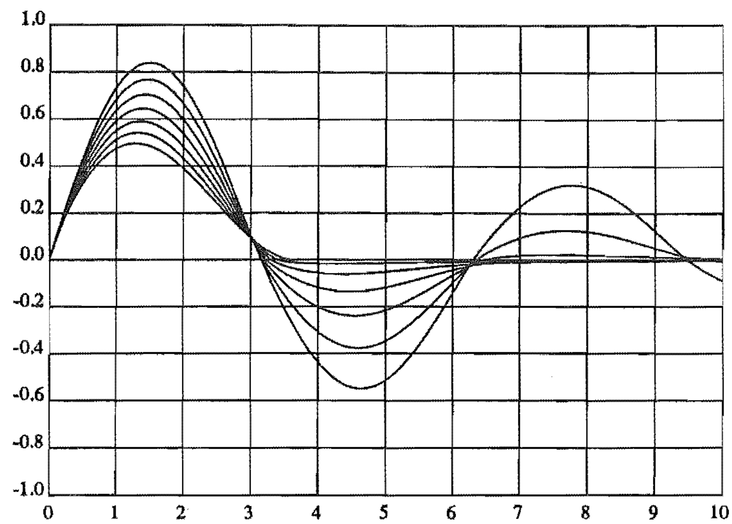


Figure 6.2 Discharge current curves. The lower curve corresponds to that of critical damping (α=0.8) and the others correspond to that of under damping, α=0.7, 0.6, 0.5, 0.4, 0.3, 0.2 respectively from bottom to top.

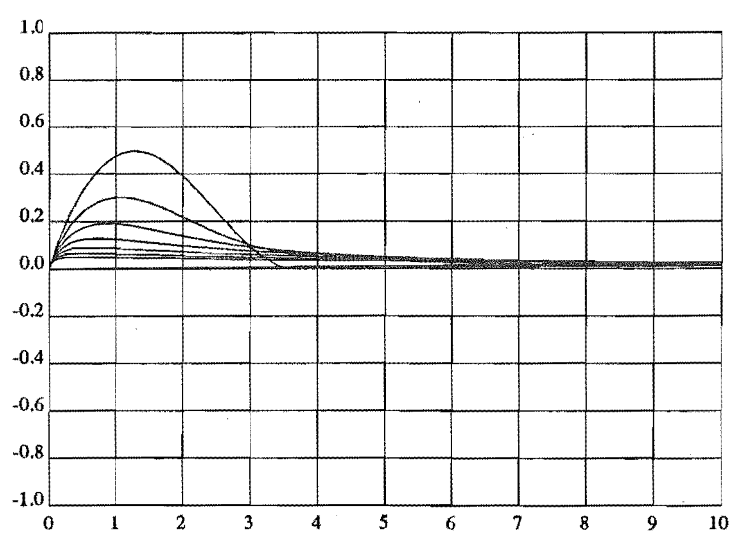


Figure 6.3 Discharge current curves. The top curve corresponds to that of critical damping (α=0.8) and the others correspond to over damping, α=1.0, 1.2, 1.4, 1.6, 1.8, 2.0 respectively from top to bottom.

We used a PASCAL on the computer to solve numerically the second order differential equation (6.7) and to give the complete time dependent current function for a flashlamp operating in such a circuit. Figures 6.2 and 6.3 show the normalised current as a function of the normalised time for various values of the damping parameter α. For delivery to the flashlamp of the highest values of instantaneous power at all times during the discharge, or for highest circuit efficiency, the current pulse should be critically damped. This occurs when α has a value of 0.8 approximately, which is considered to be optimal. For damping factors greater than 0.8, the circuit is over-damped which results in lower peak current and power (see Figure 6.3). For damping factors less than 0.8, the circuit is under-damped, which produces a current (reversal) oscillation (see Figure 6.2), resulting in higher peak currents, lower peak power and shorter flashlamp lifetime. Both under-damped and over-damped circuits result in lower efficiency of energy transfer from electrical energy to radiation.

The solution to equation (6.7) can be summarised in the three coupled equations given below. The energy stored in the capacitor is:

$$U_0 = \frac{1}{2}CV^2 \tag{6.8}$$

This equation can be rewritten as

$$V_0 = \sqrt{2U_0/C} \tag{6.9}$$

and substituting V_0 into the expression for α, we obtain

$$C = \frac{2U_0\alpha^4T^2}{{K_0}^4} \tag{6.10}$$

From the driving circuit time constant, we obtain

$$L = \frac{T^2}{C} \tag{6.11}$$

These equations are used most commonly for the design of single section flashlamp circuits. T is the time constant of the driving circuit.

Since the unit of normalised time is the driving circuit time constant

$$T = \sqrt{LC}, \tag{6.12}$$

one can relate the current pulse width at one-third peak current, $t_{\frac{1}{3}}$, to the time constant at various values of α. By comparison with Figures 6.2 and 6.3, we can see that

- $t_{\frac{1}{3}} = 2.5T$ for $\alpha = 0.6$ and 0.8
- $t_{\frac{1}{3}} = 2.7T$ for $\alpha = 1.2$

- $t_{\frac{1}{3}} = 3.2T$ for $\alpha = 1.6$

Hence our approximation of

$$t_{\frac{1}{3}} = 3T \tag{6.13}$$

$t_{\frac{1}{3}}$ is not only the current pulse duration at one-third of peak current, but it is also used to estimate radiation pulse duration.

6.3.1 Peak current

It is important to know the peak current (I_{pk}) through a flashlamp for several reasons. First, the spectral output is a function of the current density through the flashlamp. Also, there are limitations on peak current, which if surpassed, result in damage to the lamp and early failure. Equations (6.1), (6.3) and (6.4) give the instantaneous values for voltage and current at any point during the discharge, but do not indicate the peak values. Peak current is calculated approximately from:

$$I_{pk} = \frac{V_0}{Z_0 + R_t} \tag{6.14}$$

where

- $R_t = \rho l/A$,
- ρ = flashlamp resistivity = 0.015 Ω.cm for $t_{\frac{1}{3}} \leq 100\times10^{-6}$ s,
- A = cross-sectional area of flashlamp in cm^2,
- l = arc length in cm.

6.4 Trigger circuit

6.4.1 Why is a trigger circuit is needed?

The circuit in Figure 6.1 is the basic flashlamp driving circuit, but is not a practical one. This circuit gives a low repetition rate due to most xenon flashlamps having a very high breakdown voltage. In addition, the discharge occurs at random values of the voltage if there is no trigger circuit. In this case, it is difficult to achieve synchronised pulses or to have fixed repetition rate applications. Therefore, a trigger circuit is needed. Usually a brief high voltage trigger pulse is used to initiate a complete discharge through a flashlamp. Many types of triggering are used: the over–voltage, external, series and simmer techniques.

6.4.2 Over-voltage

If the initial bias voltage V_0 across the lamp is itself sufficiently high to break down the gas in the flashlamp, then the circuit will begin to discharge. Hence, uncontrolled self triggering occurs at random values of voltage as V_0 is approached. The flashlamp is therefore normally isolated from the lamp by means of a switch. The switch used is usually a mercury ignitron, a hydrogen thyratron, or a triggered spark gap. Each of these devices is itself able to be triggered. This trigger closes the switch and results in the triggering of the lamp due to 'over-voltage'. This type of trigger circuit was used in both the original and modified of Model 457 Micropulse power supply system in our clinical trials (see Chapter 7).

6.4.3 External trigger

External triggering creates a small arc streamer between the electrodes by applying a high voltage trigger pulse to thin wire wrapped around the outside of the flashlamp. The trigger pulse can also be applied to a metal bar, reflector, or cavity as long as the metal covers the entire distance between the electrodes. In these latter cases, a somewhat higher trigger voltage may be needed. The trigger pulse is supplied by a high-turns ratio transformer which can be compact and lightweight, since it has to produce high voltage but little current (100-300 mA). A finite amount of time is required for the trigger streamer to propagate down the bore of the flashlamp. The pulse duration for external triggering should be 80 ns per cm of arc length. Trigger voltages required depend on arc length, bore size, fill pressure and electrode material. External triggering provides greater design flexibility since the secondary winding of the transformer is not in the main discharge circuit. Transformers used for external triggering are less expensive and smaller than those used for series triggering. However, series triggering offers better reliability than external triggering. This manner of trigger circuit will be used for the higher pressure xenon flashlamp in further study. Planned for after to this thesisis will be completed.

6.4.4 Series trigger

In the series technique, the trigger voltage is applied directly to one of the flashlamp electrodes from the secondary of a transformer which is placed in series with the flashlamp. Again, the purpose is to create a small arc streamer between the electrodes. This facilitates triggering by lowering the voltage requirement. The series trigger transformer is larger and heavier than the external transformeer since the secondary must carry the full flashlamp current. Also, the secondary adds impedance to the circuit, and this must be considered in the circuit design. In fact, by choosing a trigger transformer having the proper value of saturated inductance, no other choke should be necessary to achieve critical damping. The trigger pulse duration for a series trigger is 60 ns per cm of arc length, and the required voltages depend on the characteristics of the flashlamp.

6.4.5 Simmer trigger

The simmer mode technique utilizes a separate power supply to maintain a dc current through the flashlamp and keep it in the ionized state. Typical simmer currents are 100 milliamps up to several amps. Flashlamp pulsing is accomplished by closing a switch, typically an SCR (silicon controlled rectifier), in series with the capacitor and flashlamp. An external trigger circuit is also required to start the flashlamp initially.

6.5 Conversion efficiency

The maximum efficiency for a xenon flashlamp is about 50 to 60%; that is, about 50 to 60% of the input electrical energy can be converted to radiant energy in the 200 to 1100 nm spectral region. However, the efficiency for a particular flashlamp depends on several factors, including fill pressure, current density and circuit design. Generally, as the current density is increased, the overall efficiency increases, but there are limits on maximum peak current, as discussed in section 6.3.1. Gas fill pressure affects conversion efficiency. A formula which is often used in technological applications to calculate approximately the fill pressure for good radiative efficiency in the visible portion of the spectrum is (ILC Technology, 1986)

$$P = \frac{225}{d}, \tag{6.15}$$

where P is the value of pressure in torr and d is the inside diameter of the flashlamp in cm. At pressures higher than P, only moderate improvements in conversion efficiency may be expected. While at pressures less than half of P, significant reductions in conversion efficiency will occur.

6.6 Flashlamp lifetime

Flashlamps do not operate at one standardised condition and therefore cannot be given a specific life rating. Instead, the lifetime of a flashlamp in terms of total number of shots is calculated for a specific application and is a function of bore size, arc length, input energy and pulse duration. The maximum input energy it can sustain is referred to as the explosion energy. Empirical studies have been conducted to attempt to predict the explosion energy for any flashlamp. The explosion energy suggested is given by

$$U_{ex} = kdl\left(t_{\frac{1}{3}}\right)^{\frac{1}{2}} \tag{6.16}$$

where

- U_{ex} = explosion energy in joules,
- $k = 90$ (constant)
- d = bore size in mm,
- l = arc length in inches,
- $t_{\frac{1}{3}}$ = current pulse width in ms.

The term explosion energy is used because it is in fact the energy at which the envelope is likely to fracture. Flashlamp lifetime is estimated by the ratio of input energy to explosion energy and is given to within an order of magnitude by

$$\boxed{\text{Lifetime}} = \left(\frac{U_{in}}{U_{ex}}\right)^{-8.5} \tag{6.17}$$

where U_{in} is input energy. From above formula, we can see that the lifetime of a flashlamp is determined by the ratio of the explosion energy to the input energy U_{in}/U_{ex}. Because of the 8.5 power relationship, at 50% of the explosion energy the lifetime is around 400 shorts. Thus most applications operate at less than 50% explosion energy.

Flashlamp lifetime is primarily limited by four factors. The first is cathode sputter, which results in the deposition of chemical and metallic deposit on the inside of the flashlamp envelope, blocking the emission of radiation from the plasma (thus giving a reduction of total flashlamp output). The second factor is aging and destruction of the the quartz envelope due to ablation, devitrification, or cracking as given by equation 6.16. The third lifetime limiting mechanism is contamination of the fill gas, eventually leading to the inability of a flashlamp to reliably trigger, ignite or simmer. Finally, lifetime is sometimes limited by failure of electrode seals.

The light output degrades gradually throughout the life of the flashlamp due to sputtering of electrode material onto the quartz walls and discolouration of the envelope. An empirical formula to estimate the flashlamp output energy degradation is given by Everett *et al* (1986). This is expressed by the relation $E_n = E_1 exp(-N/N_e)$, where E_1 is the output energy during the first pulse, E_n is the output energy during the Nth pulse, and N_e is the number of pulses required to degrade the energy to $1/e$ of its original value. It assumed that constant excitation conditions are maintained. It is generally accepted that for pulse lengths between microseconds and many milliseconds, the degradation constant is determined by a relation of the form $N_e = 2(KAt^{1/2}/U)^{8.5}$, where U is the electrical energy input to the flashlamp, A is the internal bore surface area of the discharge path in the flashlamp, t is the radiation pulse duration, and K ranges in value between 4900 and 6500 J cm^{-2} s$^{-0.5}$, with the lower figure corresponding to commercially available flashlamps.

CHAPTER 7

Clinical trials

In this chapter, we will first describe the equipment used in our clinical trials and the characteristics of the output from the xenon flashlamps for both the original and the modified system. Secondly, we will present the experimental results of our pre-clinical trials. We found that the xenon flashlamp may have a potential application of bleaching. Finally, we will describe and analyze the responses to treatments produced by the xenon flashlamp using a low energy density short pulse, a high energy density long pulse produced. Three volunteers were involved in the clinical trials, my supervisor and I had initial tests with a xenon flashlamp, while the main trials have been done on the tattoos of Ms Carol Miles.

7.1 Xenon flashlamp system or Treatment system

7.1.1 Original unit

The xenon flashlamp system consist of a Micropulse power supply unit, a xenon flashlamp and reflector. The Micropulse power supply, model 457A, and the xenon flashlamps used in our experiment were manufactured by Xenon Corp. of U.S.A, and delivered in late 1991.

The discharge circuit of the unit is a capacitive discharge circuit which is shown in Figure 7.1. The charging resistor, r, serves the function of limiting the current of the charge circuit. The storage capacitor, C with capacitance of $7.5\,\mu$F has a maximum charge voltage of 10 kV, with the result that the maximum input electrical energy of this system is 375 J. The maximum flashing frequency is 1 Hz due to the rated power for the unit of 300 watts. The capacitive discharge circuit produced the pulses with a very high peak current and power, because the pulses have a narrow length and sharp raise edge (see Figure 7.2). This system produced the pulses with $20\,\mu$s length. However, a higher peak current causes the output spectrum to shift towards the ultraviolet, and early failure of the flashlamp (Eq. 6.17). Figure 7.2

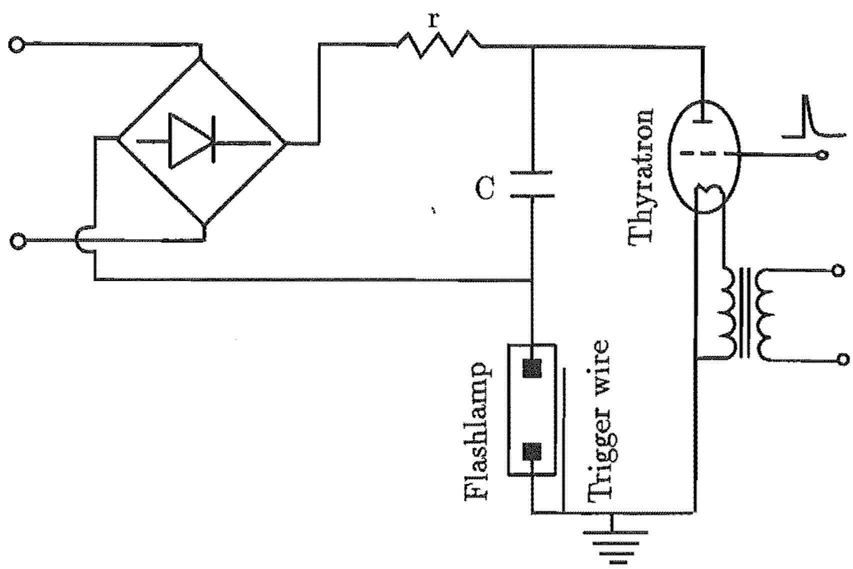


Figure 7.1 Main discharge circuit of the model 457A

shows the pulse duration and shape for the output radiation. This diagram can be taken indirectly to indicate the pulses of the current, because the pulses of current and the radiation are quite similar in duration and shape.

The over-voltage technique, which is described in 6.4.2, is employed in the trigger circuit of this unit. The thyratron used is capable of holding off high voltages between the capacitor and flashlamp. A trigger wire, properly wrapped around the flashlamp, yields a good range of operating voltage. It extends from the cathode end of the flashlamp to the anode electrode, even slightly overlapping the inside end of the anode electrode. The xenon flashlamp flashes easily after a trigger signal is supplied to the thyratron.

Two flashlamps with different sizes have been used in our clinical trials. They are named No.A and No.B in this thesis. The physical sizes inside and outside diameters, arc length, and fill pressure for the flashlamps are listed in Table 7.1. The envelope material of the flashlamps is clear fused quartz, so the output spectrum of the flashlamps contains ultraviolet.

Table **7.1** The parameters of the flashlamps

Name	Diameters	Arc Length	Pressure
No. A	0.7×0.9 cm	4 inch	200 torr
No. B	1.2×1.5 cm	3 inch	200 torr

A tight reflector coated with aluminium provides coupling output for the light.

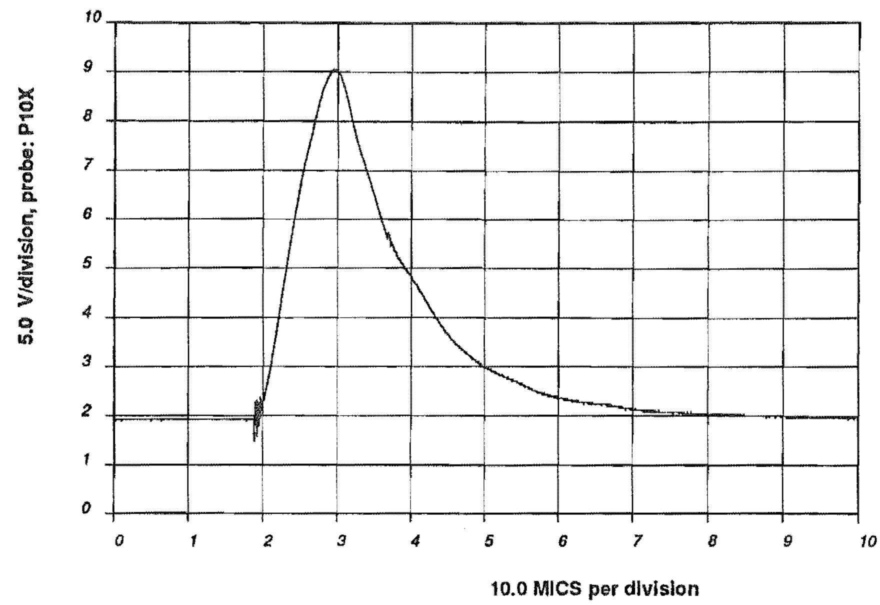


Figure 7.2 The radiation pulse shape produced by the xenon flashlamp No.B. The capacitance of the storage capacitor was $7.5\,\mu$H, and the charge voltage was 7 kV, The pulse duration at one third radiation peak was $20\,\mu$s.

The output aperture area of the reflector is 3 or 6 cm^2. The aperture has width 1 cm. The coupling output efficiency for light obtained was about 30%.

The flashlamps No.A and No.B are driven by the Micropulse power supply. The pulses produced by this system have a $20\,\mu$s pulse duration at the peak radiation and an energy density of 2.5 to 3 J cm^{-2}, when an input energy of 300 J was used. The radiation is detected by a photodiode, model MRD500 and the output signal from the photodiode is monitored by a digital oscilloscope. A typical radiation pulse shape recorded is shown in Figure 7.2.

Some failure signs appeared for flashlamp No.A and No.B, after a few tens of flashes. The failure signs included the transparent envelope glass around the electrodes of the lamp No.A changing to to a white colour, and many white spots being deposited on the inside flashlamp surface for No.B. The main reason for this was that flashlamp No.A operated at over explosion energy and flashlamp No.B operated around explosion energy. Limited input energy, which is calculated by formula 6.16, is 300 J for No.A and 500 J for No.B. The lifetime of flashlamp No.B is only about 30 shots for this situation.

Although the flashlamps operated around their limit of input energy, however, the output energy density was not sufficient to treat tattoos. On the other hand, the lifetime of the flashlamp was not long enough, and a latent danger of the possible

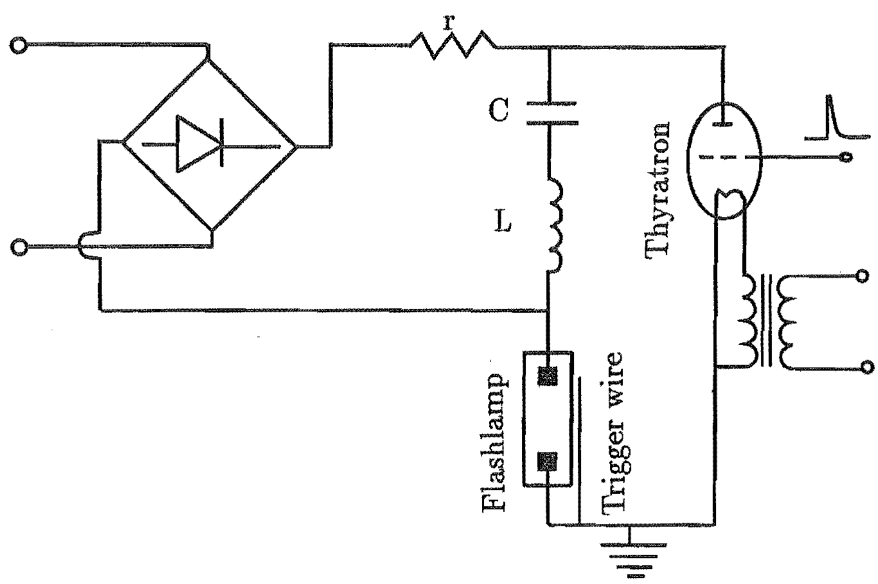


Figure 7.3 Modified discharge circuit

explosion of the flashlamp, also existed for the volunteers.

7.1.2 Modified unit

Higher energy density cannot be expected from the original unit, because the restrictions on pulse duration and flashlamp explosion energy are linked to each other (see formula 6.16), For shorter pulse durations, the explosion energy is lower for a particular flashlamp. I redesigned the discharge circuit in order to obtain higher energy density and to extend the lifetime of the flashlamp.

I designed and made a inductor of 600 μH, and inserted it between the xenon flashlamp and storage capacitor. This inductor has 75 mm in diameter and 220 mm length, and 158 turns of copper wire of 1 mm wound on uPVC pressure pipe. The capacitance of the storage capacitor was increased from 7.5 μF to 120 μF. The capacitor has a maximum charge voltage of 8 kV. The modified discharge circuit is shown in Figure 7.3. A lifetime of 2500 shots is expected (Eq. 6.17), because the explosion at this pulse length is now 2000 J for flashlamp No.A. The radiation pulse we obtained from this system has an energy density of 8 J cm^{-2} and pulse duration of 550 μs (see Figure 7.4) at one third peak radiation, when input energy of 800 J was used. The measurement method for the radiation pulse shape is as described above.

However, the discharge circuit was operating under-damped. The damping factor for flashlamp No.A was 0.15 which is less than that for critical damping. Normal design for the same output suggested that the capacitance of the storage capacitor is 900 μF, inductance is 45 μH and charge voltage is 1.7 kV. The choice we have is

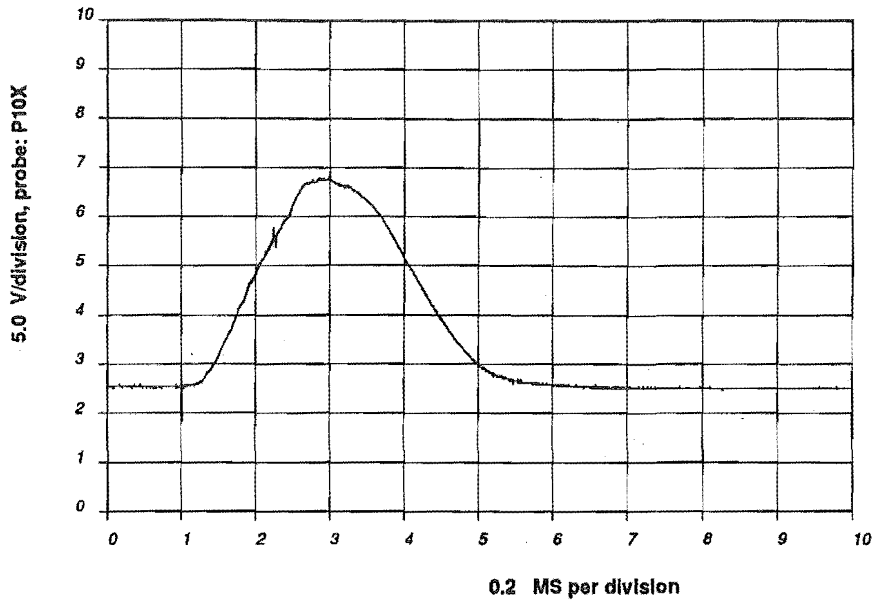


Figure 7.4 The radiation pulse shape produced by flashlamp No.A when driven by the modified discharge circuit. The charge voltage was 3.6 kV, capacitance was 120 μF and inductance was 600 μH. The pulse duration at one third radiation peak was 550 μs.

restricted by our present choice of capacitors.

7.2 Experiments of Pre-clinical trials

Some experiments were done before clinical trials took place in order to understand the output characteristics of the xenon flashlamps. We exposed red paper, photocopies, coloured advertisement paper and paper smeared with charcoal using the xenon flashlamps.

Figure 7.5 shows two samples which were exposed with xenon flashlamps. Sample A was irradiated before we first clinical trial with flashlamp No.B which was driven by original unit. Sample B was exposed before second clinical trial with flashlamp No.A which was driven by modified unit. In the former case, the light pulse had an energy density of 2.8 J cm^{-2} and 20 μs pulse length. In the latter, the pulse used had a energy density of 8 J cm^{-2} and a pulse duration of 550 μs. It can be observed that nearly all red colour has gone for both samples, the effect on sample B being particularly strong. A photocopy, an offset printed page (the newsletter of the Physics and Astronomy Department and the Chronicle of Canterbury University), were cut into strips together with red paper and exposed by flashlamp No.A, the pulse used had a duration of 50 μs. The distance between the pieces of photocopy and the xenon

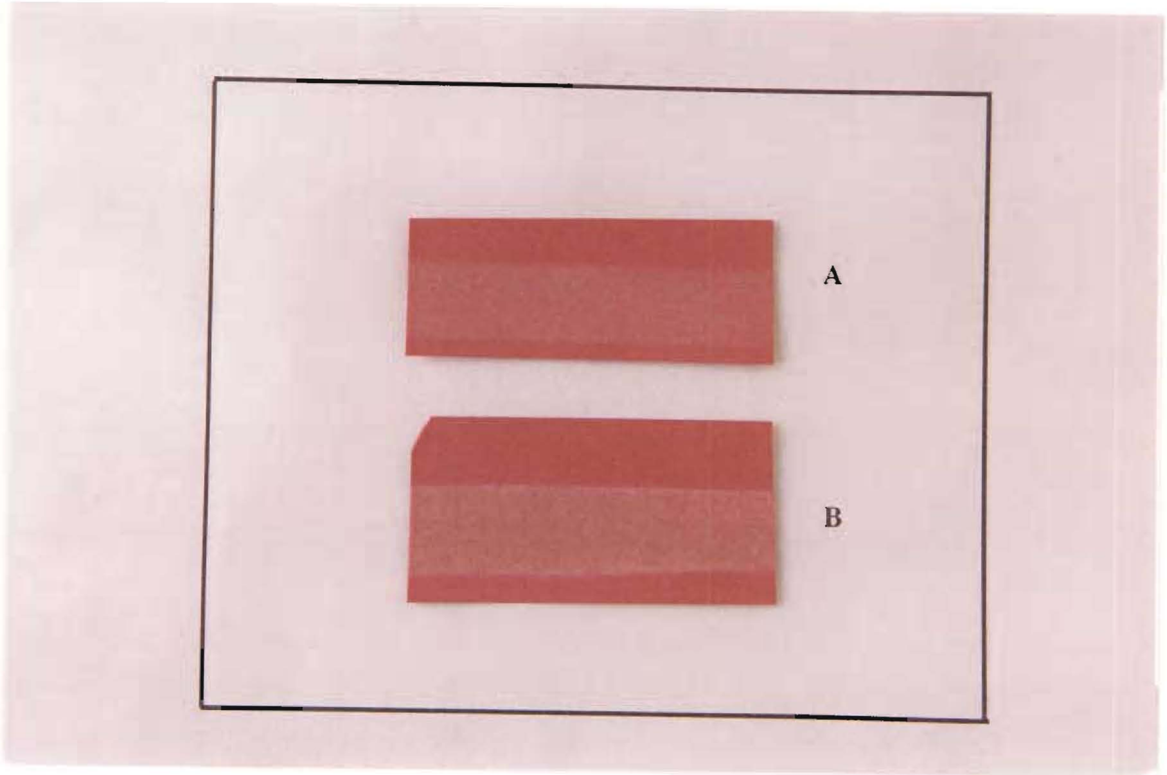


Figure 7.5 Bleaching of red paper using the flashlamps. Sample A was exposed by a pulse with 2.8 J cm^{-2} and 20 μs pulse length, Sample B was irradiated by a pulse with 8 J cm^{-2} and 550 μs pulse length.

flashlamp surface was 0.5 cm. After one exposure, about 30% of the black colour of the characters has gone (see Figure 7.6 A) when the input electrical energy of the system was 240 J. After two exposures, at least 50% of the black colour of the characters has gone (see figure 7.6 B), the same pulse characteristics were used in the later experiment. Figure 7.7 shows that more than 50% of the black colour of the characters has faded after one exposure when higher energy density was used. A pulse from a xenon flashlamp with energy density of 2.8 J cm^{-2} and pulse duration of 50 μs was used to illuminate the paper smeared with charcoal and about 40% of the charcoal disappeared from the paper. A wisp of smoke was noted in the reflector, and very fine charcoal particles were deposited on the tube surface.

After irradiation with flashlamp No.A, about 50% of various colours has been bleached from coloured advertisement paper. The radiation pulse used in this experiment had an energy density of 3.0 J cm^{-2} and 50 μs pulse length.

Observation of these experimental results suggest a potential application for the xenon flashlamp. It could be used for bleaching any colours and typescript, especially used for non-contact or hard to contact bleaching, for example where the samples are in the vacuum.

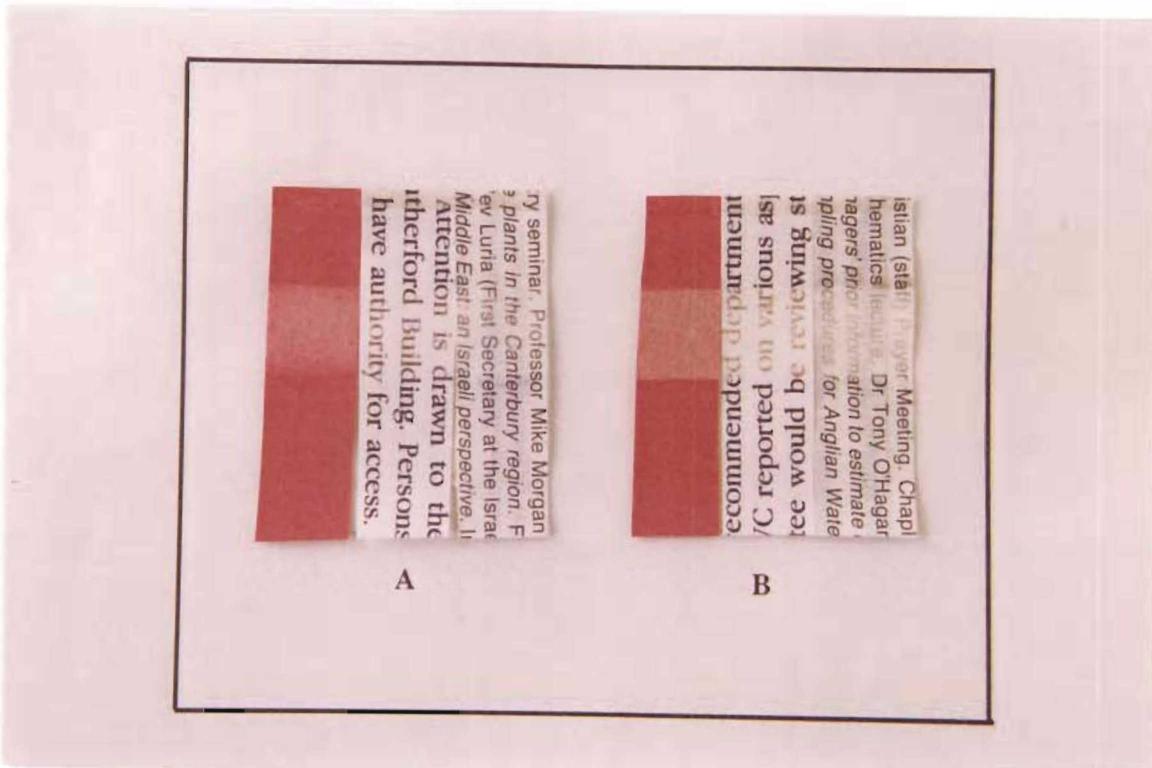


Figure 7.6 Bleaching of the black colour of the typescript.

7.3 Clinical trials

7.3.1 Treatment with low energy density and short pulse length

In the first session of clinical tests, we chose flashlamp No.B operating in the original system. Input electrical energy was 240 J to 303 J. The pulses produced by this system had 20 μs pulse duration and energy density about 2 to 2.8 J cm^{-2}. The coupling output aperture was 6 cm^2 (1 cm $\times$6 cm), and 3 cm^2 of radiation area was used for the trials. The distance of the treatment area to the flashlamp surface was 1 cm. There was no UV filter in this experiment.

The first test was conducted on normal caucasian lightly tanned skin on the forearm of my supervisor. The input electrical energy of 240 J was used. Immediately after exposure of the skin, the odour of burning hair was smelt and the treated area appeared white. After 2 hours, heavy erythema appeared and lasted up to about 20 hours, giving a sensation like sunburn. Erythema on the exposure area disappeared gradually, and the flashed area return to normal after two days.

I have had a blue ink spot tattoo of 0.2 cm in diameter on the left wrist. This was made by a pen thirty years ago. A 3 cm^2 area of asian yellow skin including the blue spot was exposed to a light pulse, and the input electrical energy was 303 J. Output energy density was about 2.8 J cm^{-2}. The immediate response was that the

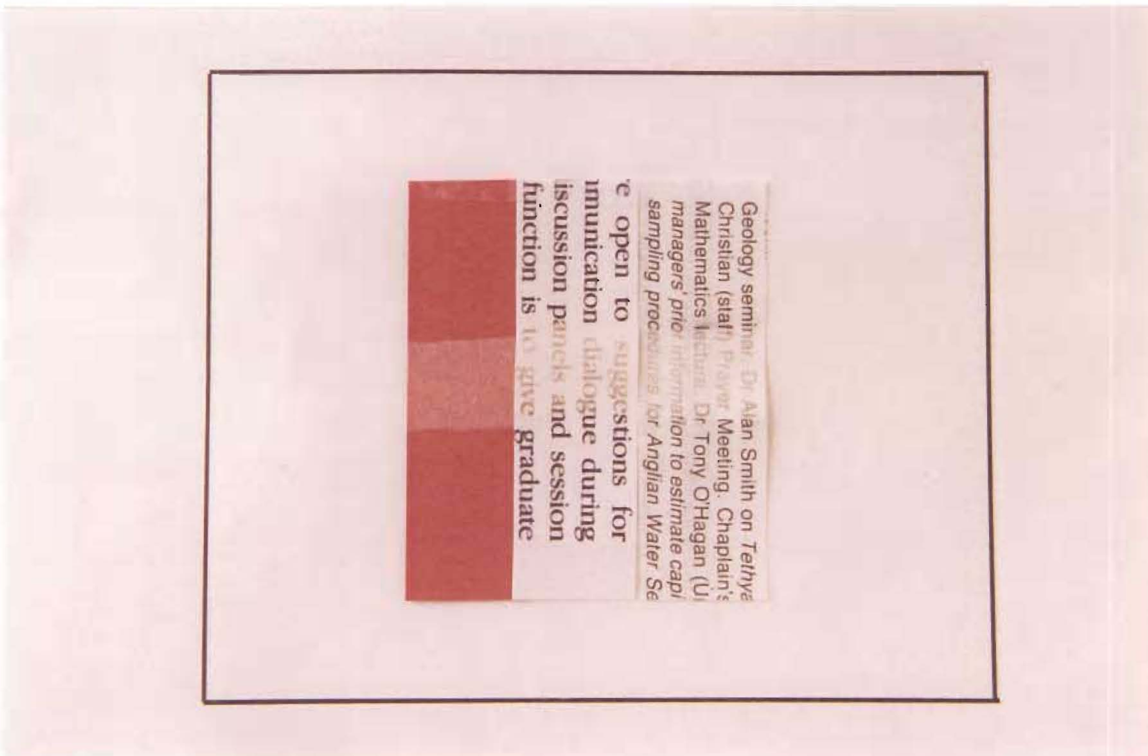


Figure 7.7 Bleaching of the black colour of the typescript. Input electricity energy of the system was 350 J, the pulse length was 50 μs.

exposed area turned grey-white. The blue ink spot was hard to distinguish. One hour after irradiation, slight erythema appeared and it increased during the next 10 hours. Slight oedema also appeared and sensation like that from a steam burn. After 20 hours, most of the erythema disappeared, but the flashed area could still be seen. The skin exposed was shiny and tender, the blue ink spot looked lighter than that before exposure. The irradiated area turned to normal within a week after, and the blue ink spot still persisted.

For latter trials, Ms Carol Miles and has caucasian skin, was a volunteer. A 3 cm^2 tattooed area of the inner leg including red and black tattoo and normal colour skin was chosen for the clinical trials. The black tattoo has a heavier pigmentation than that of the red tattoo. An input energy of 303 J was used. The immediate response of the exposure was that the skin surface appeared grey white. A pricking sensation was felt, which dissipated in 20 minutes. Very light erythema and slight oedema occurred on the treatment day, the erythema and oedema increased over the next 24 hours, and were associated with treatment area itches. At 44 hours, we noted that both tattooed and non-tattoo areas, appeared as at 24 hours, with a little greater response in black vs clear or red pigmented areas.

The above experiment results shows that the 20 μs pulse with energy density of

$2.8\,J\ cm^{-2}$ did not produce lasting damage to the treatment area, and did not affect the surrounding tissue. As well, the above results indicated that the response of the exposure to xenon flashlamp in yellow skin is less than that in the white skin. The response in tattooed areas is greater than that of normal skin, because tattoo pigments cause tattooed skin to have a greater absorption than normal skin. The above results suggests that the energy density of the light pulse used was not sufficient to cause irreversible damage to the pigment clusters.

7.3.2 Clinical trial with long pulse and high energy density

In the second clinical trial, we chose flashlamp No.A which operated in the modified system with input electrical energy 800 J, The pulses produced by this system had a pulse duration of $550\,\mu s$ and a output energy density of $8\,J\ cm^{-2}$, a rectangular aperture of $10\,mm\times30\,mm$ being used.

The treatment area in the inner left leg of the volunteer again included red and black tattoo and normal skin. Immediately upon exposure the irradiation site became grey white, and associated with it was an odour of burning hair. This grey white colour disappeared within 30 minutes. 'Stinging sensation like a mild scald was felt' said the volunteer. This opaque white appearance of the skin may be caused by the formation of vacuoles in the dermis probably due to the production of steam, or absorption of energy by melanin in the epidermis which causes the melanocytes to 'balloon', the nuclei becoming hyper-chromatic. This effect may increase the scattering of the incident light.

Three small blisters occurred, all in the tattooed area, and there was erythema in the non-tattooed area within 24 hours. One blister burst by itself and its area was squamous, the other two were drained by the volunteer by pricking their edges with a scalpel blade. The area was bandaged with an elastoplast, after being protected with an antibiotic ointment containing steroids. Thirty hours after exposure, the volunteer reported that the treated area exhibited a raised distention about 2.0 mm high, $50\,mm\times55\,mm$ in area. The response shown was remarkably more intense in the tattooed skin than in the surrounding skin. The tattoo pigment in tattooed area absorbed more energy than the surrounding tissue did, just as expected. However, a $550\,\mu s$ pulse length produced excess thermal conduction, so that heavier erythema was produced in non-tattooed skin. Another probable reason for production of erythema in non tattooed skin is that no UV filter was used.

The distention was gone in 3 days. After 6 days, the exposed area had a light scab, and healed in 8 days, which indicated that the dermis was not severely damaged. Two month after treatment, we noted that there was little or no loss of pigment evident. The skin surface was still shiny and delicate. There was a small amount of hyper-pigmentation on the exposed un-pigmented skin.

The clinical response to a xenon flashlamp was very close to that of produced by a Q-switched ruby laser. Scheibner *et al* described the response to the treatment of tattoo with a Q-switched ruby laser. Immediately after laser exposure, the skin turns white and remains this colour for 10 to 20 minutes. The treated area then turns red and shows some swelling. The treated area will feel like a sunburn for approximately 30 to 60 minutes. In some patients, vesiculation occurred at sites with thin skin. Vesicles were replaced generally in 1 to 2 days by a fine crust. The treated area healed typically within 10 to 14 days, but the skin remained slightly red for an additional 1 to 3 weeks. The same response also reported by Taylor *et al* (1990) and Reid *et al* (1983).

In our clinical trials on exposed skin our flashlamp gave a very similar response to the Q-switched ruby laser, which indicates that the energy density of $8\,\mathrm{J\ cm^{-2}}$ is very close to the treatment threshold, and indicates that the pulses with $100\,\mu\mathrm{s}$ length might be useful.

CHAPTER 8

Conclusion

This thesis investigated the mechanism for the favourable results of the Q-switched ruby laser removal of tattoos. We postulate that this laser works by selective photothermolysis.

This thesis argues that three factors have to be considered for the successful application of the selective photothermolysis technique. The first condition is a sufficient spectral match between radiation and targets. The targets must have a greater optical absorption at the spectral range of the radiation than their surrounding tissue. The second condition is that the period of energy delivery must be shorter than that of significant thermal conduction. The third condition is that there is a sufficient energy density to generate the thermal effects required.

The model of processes for tattoo removal proposed by Reid *et al* and Taylor *et al*, to heat tattoo pigment to generate very high temperature so that conversion of carbon into carbon monoxide or carbon dioxide, may be incorrect.

As a results of this studies, a new method for removal of tattoos is proposed. This thesis report attempts at implementing the method. A high power xenon flashlamp is employed for the first time as an optical pulse source for a cosmetic purpose. The expected advantages of this method are the low cost, less than one tenth of the cost of the Q-switched ruby laser, and good spectrum matching between absorption of tattoo dyes and radiation from the xenon flashlamp.

Histological studies show that very few tattoo pigment particles are suspended in the skin, rather the tattoo pigment occurs in small and big clusters. The size of pigment clusters varies from 1μm to 20μm and their distribution in depth is from 0.1 mm to 1 mm. We propose that it is not necessary to rupture individual tattoo pigment particles, so that a nanosecond order pulse duration for tattoo removal is not necessary.

Theoretical values for the illumination time and energy intensity required to break up tattoo pigment clusters are suggested. The pulse duration ought to be less than

$100\,\mu s$. The energy density should be higher than $0.5\,J\ cm^{-2}$ when tattoo pigment clusters are exposed directly.

Absorption spectra for eight tattoo dyes are presented in this thesis. As a result a very good spectrum match in the visible between the radiation of the xenon flashlamp and the absorption of the tattoo dyes is revealed. This verifies that the radiation of a xenon flashlamp satisfies the spectrum matching factor for selective photothermolysis. As well, a UV filter with high visible light transmission is obtained.

Every effort has been made on the xenon flashlamp system to make the output characteristic of it to satisfy proposed treatment parameters. In our clinical trials, the pulses with $20\,\mu s$ pulse duration and energy density of $2.8\,J\ cm^{-2}$ gave a little greater response in tattooed area than clear skin, and did not affect the surrounding tissue. The pulse with $550\,\mu s$ length and $8\,J\ cm^{-2}$ gave a more intense response in the tattooed area than its surrounding tissue, but erythema occurred in the non-tattooed skin area. The pulses, with short pulse length and low energy or with long pulse length and high energy, did not produce lasting damage to the treatment area. The response of the treatment area immediately and some hours after was very close to that produced by the Q-switched ruby laser.

The results of our theoretical calculation and clinical trials suggested that pulses of the order of 100 microsecond are available for the treatment of tattoos without damage to the tattooed area and its surrounding tissue. They also suggested that energy density of $8\,J\ cm^{-2}$ is probably near the treatment threshold for pulses of this length.

We have asked Xenon Corp. to provide high fill pressure xenon flashlamps with thicker wall. This should allow us to produce the pulses with $10\,J\ cm^{-2}$ and $100\,\mu s$.

As a result of the theoretical work and clinical trials, and experience with the Q-switched ruby laser removal of tattoos, we are hopeful that such pulses will treat professional tattoos with the same effectiveness as the Q-switched ruby laser, namely substantial lightening or complete fading of a tattoo after 3 to 8 treatments.

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